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*Journal*

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# THE ROYAL AERONAUTICAL SOCIETY

APRIL 1953

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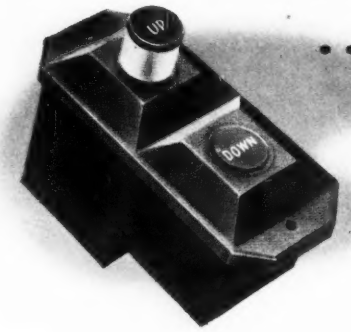


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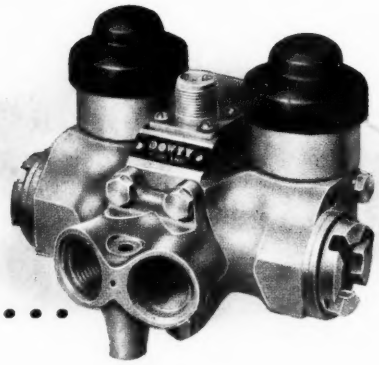


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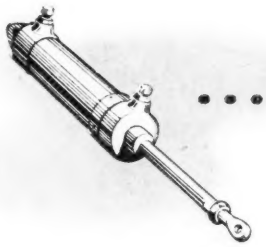

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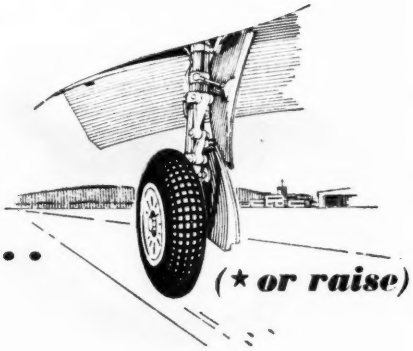

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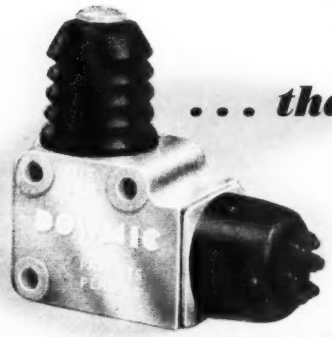

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*Journal of*

# THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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*All communications for publication in, and advertisements for, the Journal should be addressed to the Editor, Joan Bradbrooke, A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary, A. M. Ballantyne, T.D., B.Sc., Ph.D., A.F.R.Ae.S.*

*None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless stated otherwise.*

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# NOTICES

## Annual General Meeting 7th May 1953

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday, 7th May 1953, at 5.30 p.m. in the offices of the Society, 4 Hamilton Place, London, W.1.

### Agenda

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets and Income and Expenditure Accounts of The Royal Aeronautical Society and Aeronautical Trusts Limited for the year ended 31st December 1952.
3. To receive the names of those elected to Council for the years 1953-56.
4. To announce the names of Fellows elected by the Council in accordance with By-Law 4.
5. To elect the Auditors for the year 1953.
6. Any other business.

By Order of the Council.
A. M. Ballantyne,
Secretary.

NOTE—In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

## Members' New Appointments

J. Elsner (*Associate Fellow*) formerly Chief of Flight and Operations Engineering of Air France Long Range Base (Orly) has recently been appointed Research and Engineering Manager for Air France in North America.

W. H. Hambrook (*Fellow*) has been appointed Technical Director of Short Brothers and Harland Ltd.

James Hodge (*Associate Fellow*), Senior Consultant with Power Jets (R. & D.) Ltd. at Farnborough, has been appointed visiting Professor of Mechanical Engineering at Columbia University.

N. J. Howard (*Associate Fellow*) has been promoted to the Professional Engineers Grade (Engineer III) of the Ministry of Supply, at A.E.R.E., Harwell.

C. H. Latimer-Needham (*Fellow*) has been appointed Chief Executive of the Aeronautical and Engineering Divisions of the R.F.D. Company Ltd. He is retaining his connections with Flight Refuelling Ltd. as a Consultant.

J. S. Linton (*Graduate*) has been appointed Assistant Resident Technical Officer at Vickers-Armstrongs Ltd., Weybridge.

Group Captain W. J. Macken (*Associate*) has recently been appointed Deputy Director of Armament Engineering at the Air Ministry.

A. G. Shove (*Associate Fellow*), formerly of de Havilland's, has recently joined the Aircraft Sales Department of Blackburn and General Aircraft Ltd.

E. Szomanski (*Associate Fellow*) has recently been appointed a Senior Lecturer in Fluid Dynamics at the University of Tasmania.

G. R. Volkert (*Fellow*) has recently been appointed to the Board of Handley Page Ltd.

## Associate Fellowship Examination

The next Associate Fellowship Examination will be held in the offices of the Society on the 18th, 19th and 20th May 1953. All candidates who have entered for the Examination will be informed individually of the detailed arrangements.

## 1953 Garden Party

This year the Society's Aeronautical Garden Party will be held at Hatfield Aerodrome (by kind permission of the Directors of de Havilland Aircraft Ltd.) on Sunday 14th June 1953.

An application form for tickets will be sent to all Home Members.

## British Commonwealth and Empire Lecture

The Ninth British Commonwealth and Empire Lecture will be delivered by Sir Hubert Walker, C.B.E., on "Some Problems in the Development of Air Transport in West Africa" on Thursday, 12th June 1953, at 6 p.m. at the Royal Institution, 21 Albemarle Street, W.1.

Following the Lecture a Reception will be held at 4 Hamilton Place for members and their ladies.

Full particulars will be sent to all members.

## The Aeronautical Quarterly—Vol. IV Part II

Part II, Volume IV of The Aeronautical Quarterly is now available from the offices of the Society at 7s. 9d. (including postage) per copy to members, or 10s. 3d. to non-members. The contents are—

| | |
|---|---|
| On the Noise Emanating from a Two-Dimensional Jet Above the Critical Pressure | *Alan Powell* |
| Some Aspects of Laminar Boundary Layer Separation in Compressible Flow with no Heat Transfer to the Wall | *G. E. Gadd* |
| Buckling of Oblique Plates with Clamped Edges Under Uniform Compression | *W. H. Wittrick* |
| A Note on the Theory of the Constant-Area Mixing of Compressible Flows as Applied to High-Speed Wind Tunnel Design | *F. G. Irving* |
| A Note on the Performance of Ducted Fans | *Bryan Thwaites* |
| On the Resistance of Screens | *K. E. G. Wieghardt* |
| Flow Changes in Gases in which Mass and Impulse are Conserved | *L. G. Dawson* |

## Income Tax

In response to numerous inquiries from members with regard to a rebate on Income Tax for their subscriptions, the following is a copy of a letter received from the Principal Inspector of Taxes.

Ref. H.R.S. 34/C.I. 4420/63.

Dear Sir,

Further to your interview with Mr. Stonely at this office on the 19th July, I am now in a position to inform you that the Board of Inland Revenue will not raise objection to the allowance as an expense for Income Tax purposes of annual subscriptions paid by members who are:—

(*i*) Assessable under Schedule D of the Income Tax Acts in respect of professional or trading profits, subject to the decision of the Commissioners who make the assessment that such subscriptions are sufficiently closely related to the business on: or

(*ii*) Assessable under Schedule E in those cases only in which continual membership of the Society is an essential condition of the terms of appointment.

Yours faithfully,
(Signed) Geo. Wilcock,
*Principal Inspector of Taxes.*

## *DIARY*

### LONDON

April 22nd
GRADUATES' AND STUDENTS' SECTION. Aircraft Accident Investigation. H. Caplan. 4 Hamilton Place, W.1. 7.30 p.m.

April 23rd
MAIN LECTURE at GLASGOW. Civil Jet Operations. Captain A. M. Majendie. The Royal Technical College, Glasgow. 7.30 p.m.

May 21st
JOINT MEETING ON AERONAUTICAL ACOUSTICS (ALL DAY). Joint Meeting with the Acoustics Group of the Physical Society on Aeronautical Acoustics—in particular Jet Noise. At the Institution of Mechanical Engineers, Storey's Gate, S.W.1. 10 a.m. to 6 p.m.

June 11th
Ninth BRITISH COMMONWEALTH AND EMPIRE LECTURE. Royal Institution, Albemarle Street. 6 p.m.

### BRANCHES

April 15th
**Hatfield**—Fatigue: What It Is and Ways of Reducing its Incidence. Major P. L. Teed. Senior Staff Mess, de Havilland Aircraft Co. Ltd., Hatfield. 7 p.m.
**Preston**—Annual General Meeting, followed by a Brains Trust. Assembly Hall of the Technical College, Corporation Street, Preston. 7 p.m.
**Reading and District**—Meteorological Service for B.O.A.C. Comet Operation. E. Chambers. The Abbey Gateway Room, Abotts Walk, Reading. 7.45 p.m.
**Southampton**—Aircraft Maintenance. B. S. Shenstone. Institute of Education, University of Southampton. 7 p.m.

April 17th
**Birmingham**—Adhesion and Adhesives. E. Love. Chamber of Commerce. 7.30 p.m.

April 20th
**Halton**—Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

April 21st
**Belfast**—Annual General Meeting. New Hall, Kensington Hotel, College Square East, Belfast. 7 p.m.

April 22nd
**Coventry**—Annual General Meeting and Films on Lubrication, by courtesy of Esso. Wine Lodge. 7.30 p.m.

April 23rd
**Glasgow**—MAIN LECTURE—Civil Jet Operations. Captain A. M. Majendie. Royal Technical College, Glasgow. 7.30 p.m.

April 24th
**Hatfield**—Annual Dinner.

April 27th
**Halton**—Bird Flight. Captain J. L. Pritchard, C.B.E. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.
**Henlow**—Student Members' Premium Lectures. R.A.F. Technical College, Henlow. 7.30 p.m.

May 4th
**Derby**—Combustion Chambers—Accident or Design? S. L. Bragg. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.
**Halton**—Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

May 6th
**Weybridge**—Annual General Meeting. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

May 11th
**Halton**—Pneumatic and Hydraulic Brakes and Tyre Maintenance. W. S. Saunders and F. W. Paterson. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

May 13th
**Chester**—Annual General Meeting. Grosvenor Hotel. 7.30 p.m.
**Hatfield**—Annual General Meeting. Senior Staff Mess, de Havilland Aircraft Co. Ltd., Hatfield. 7 p.m.

May 18th
**Halton**—Junior Members' Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

May 29th
**Glasgow**—Problems in the Design of Highly Swept Aircraft. G. H. Lee. Royal Technical College. 7.30 p.m.
**Leicester**—Gas Turbine Development. A. J. M. Peace. College of Technology. 7.15 p.m.

### MARCH JOURNAL—A CORRECTION

A correction from Colonel Jessop to his reply to the Discussion following his Lecture on "The Scope and Limitations of the Photoelastic Method of Stress Analysis" (March 1953 JOURNAL) is published in the Correspondence Section of the April JOURNAL.

### INTERNATIONAL AERONAUTICAL CONGRESS ON PRODUCTION—PARIS, 26TH JUNE-6TH JULY 1953

On the occasion of the 20th International Aeronautical Exhibition which will be held in Paris from the 26th June-6th July 1953, the Association Française des Ingénieurs et Techniciens de l'Aéronautique are holding an International Aeronautical Congress on the Production of Air Frames.

Members of the Society and others who wish to attend this Conference, and if possible submit papers on the subject of Aircraft Production, are invited to do so. All communications should be addressed to Monsieur J. Jarry, President, Association Française des Ingénieurs et Techniciens de l'Aéronautique, 6 Rue Cimarosa, Paris XVI.

### ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

*Associate Fellows*

Robert Bridge (*from Graduate*)
Harold Gordon Chapman
John Henry Richard Chubb (*from Associate*)
William Gascoygne Clennett (*from Graduate*)
William Robert Sands Davidson
Norman Adrian de Bruyne
Ercole Trigona Della Floresta
Tore Ragnar Gullstrand (*from Associate*)
Norman Holey
Alastair Munro Mackie (*from Graduate*)
Kurt Werner Mangler
Edward Lucas Mole
George Moss
Leslie Joseph Murrin (*from Graduate*)
Victor Charles Otter (*from Associate*)
Walter Thomas Peters
Edward George Preston
Basil Robert Edwin Riddaway (*from Graduate*)
William Bertram John Shakespeare
Trevor Edwin Arthur Stevenson (*from Graduate*)
Georges Ernest Andre Thomann (*from Graduate*)
Alan Hansford Walker
Norman George Horace Weeks
Granville Harding Williams
Joseph Charles Wordsworth (*from Graduate*)

*Associates*

Leslie Stapleton Henthorne
William Henry Higgs
Ronald James Sullivan
Hereward Archibald Wimborne

*Graduates*

Said Abu-Mostafa
Frederick Anthony Herbert Ashmead (*from Student*)
Derrick George Beavis
David Alan Hughes Bird (*from Student*)
Maxwell Kenneth Bull
Lancelot John Hope (*from Student*)
Stanislaw Leon Kochanski
Brian Marshal Laven
William Henry Napthine (*from Student*)
Derek Wardle Pickston (*from Student*)
Sheikh Mohammed Saeed
Brian Sparks

*Students*

James Frederick Allen
John Elmes
Peter Stanley Jaffray
Bryan Sturton Jennings
John Gwillim Latham
Graham Victor Lobley
Ernest Capel Martin
Hugh Anthony Money
Philip Arthur Mervyn Wixon

### ACKNOWLEDGMENTS

The Council acknowledge with thanks the return of back numbers of the JOURNAL from Major G. H. Abell, *Fellow;* A. D. Scarlett, Esq., *Associate Fellow;* J. D. Walsh, Esq., *Associate Fellow* and Squadron Leader E. F. G. Worthy, *Associate.*

*Journal of The Royal Aeronautical Society*

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 57 APRIL 1953 NUMBER 508

# Titanium - A Survey

by

P. L. TEED, A.R.S.M., M.I.M.M., F.R.Ae.S.

The 863rd Lecture to be given before the Royal Aeronautical Society was on "Titanium —A Survey," by Major P. L. Teed, A.R.S.M., M.I.M.M., F.R.Ae.S., on 29th January 1953 at the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1. Mr. G. H. Dowty, F.R.Ae.S., President of the Society, presided, and introduced Major Teed, who, after service in the R.N.A.S. and R.A.F. in the 1914-18 War, was appointed Head of the Gas and Chemistry Sections of the Inter-Allied Aeronautical Commission of Control, Germany, in 1918 and in 1921 was also appointed President of the Inter-Allied Commission of Control, Danish Plebiscite Zones; in 1924 he joined the Airship Guarantee Company as principal assistant to B. N. Wallis and on the completion of the R.100 joined Vickers Aviation Ltd. at Weybridge. In 1938 he was appointed first Chief Inspector of Materials at the Air Ministry, and during the 1939-45 War served first as Deputy Director of Material Production in the Ministry of Aircraft Production and then as Metallurgical Adviser to the Ministry and to the British Scientific Office in Washington. Major Teed rejoined Vickers-Armstrongs Ltd. in 1945 as Deputy Chief of Aeronautical Research and Development. Since the War he has lectured in the United States on several occasions and in 1951 he was a member of a team of eight which went to the United States under the auspices of the Anglo-American Council on Productivity to study and report on the conservation of strategic materials.

## Introduction

Before making an appreciation of present knowledge about a single metal, it is not inappropriate to say something of all metals, for the ever-increasing tempo of material civilisation has largely depended on man's increasing knowledge of these constituents of his World. His first discovery in this field was copper. To it and to its alloys he gave an exclusive allegiance for some 100 generations, then about 3,000 years ago iron became, and still continues to be, the predominant metal of his needs.

In the eighteenth century, when alchemy finally gave way to the logic of scientific thought, the metals employed by man for purposes other than currency and decoration were practically confined to iron, copper, tin, zinc, mercury and lead. Today, when over seventy metallic elements are known, only a small number of these are used by the engineer. His mechanism and structures are mostly made of the alloys of only two metals, copper and iron. Should he, on the other hand, exercise a wider choice, then his basic metals are only increased to four, and of these, the two additions, aluminium and magnesium, have come into being as commercial materials within the lifetime of many now living.

This brief survey raises a question—how is it that with so many of these elements available to him the engineer uses so few? In the whole series of British Standards Aircraft and D.T.D. Specifications, but 26 metals are even mentioned, and some of these are included solely because their presence, in a particular alloy, is deemed disadvantageous.

There is no short answer to this query. Some are not employed because their properties are unknown or, if known, are not appreciated. Others find their places in museums rather than in industry, because of the difficulty with which they are extracted from their ores. Yet others are unused because of the rarity of the deposits in which they occur. Some, but not all, of these influences have contributed to the Cinderella-like past of Titanium.

## Historical Note

In 1789, the Rev. William Gregor detected the existence of this metal in a specimen of black sand from Menachan, Cornwall. Not unreasonably he gave to it the name, Menachite. Then, five years later, the German chemist, Klaproth, found an identical substance in another mineral, having a different geographical origin. Unimpressed by the appropriateness of Gregor's nomenclature, but greatly impressed by the strength of its chemical bond with other elements, which he likened to that of a Titan, he gave to the metal the name by which it is known to this day.

Because of the extreme difficulty of producing titanium from its ores, for something like a century after

its discovery it remained in almost complete obscurity; then Moissan, in the course of his many experiments in the electric arc furnace, again produced the metal. Thus made, it was a scientific novelty but not an engineering material. It lacked, doubtless due to its containing about 2 per cent. carbon, that essential quality, ductility. Finally in 1910, Hunter[1], using a reducing process analogous to, but by no means identical with, that employed today, succeeded in obtaining relatively pure metal possessing a fair measure of ductility. For another thirty years, however, it failed to attract the attention of the engineer, and might still be unknown to him had it not been for Kroll[2], who, in 1940, showed how it could be produced in quantity; some time later, Dean[3] and others indicated some of its engineering possibilities.

## Occurrence of Titanium in Nature

Titanium, unlike the metals first known to man, such as gold, silver, mercury, copper and iron, is not found in the elemental state. At a later stage, when the chemistry of the metal is touched upon, it will be appreciated how this comes about. It might, however, be mentioned that, at temperatures existing when the World was very young, its chemical affinity for other elements, which over a century and a half ago so greatly impressed Klaproth, made impossible its existence in an uncombined state.

While titanium is still something of a novelty, in combination with other elements, it is widely distributed in the earth's crust. This is shown in Table I.

TABLE I

SOME METALLIC CONSTITUENTS OF THE EARTH'S CRUST, PARTS PER MILLION

(*Principles of Geochemistry*, Brian Mason, Chapman & Hall, 1952)

| | |
|---|---|
| Aluminium | 81,300 |
| Iron | 50,000 |
| Calcium | 36,300 |
| Sodium | 28,300 |
| Potassium | 25,900 |
| Magnesium | 20,900 |
| **TITANIUM** | **4,400** |
| Manganese | 1,000 |
| Rubidium | 310 |
| Strontium | 300 |
| Chromium | 200 |
| Nickel | 80 |
| Copper | 70 |
| Tin | 40 |
| Lead | 16 |
| Uranium | 4 |
| Silver | 0·1 |

## Titanium Minerals and Their Distribution

Most titanium minerals consist of its di-oxide, $TiO_2$, or combinations of this oxide with that of another element, or elements, such as iron, or silicon.

Table II gives the names, chemical composition and crystalline form of the chief titanium minerals.

While only trifling quantities of titanium minerals have so far been used for the production of the metal, they have long been of commercial importance, for they are employed in substantial quantities in such diverse fields as the manufacture of porcelain glaze, heat resisting glass, cladding of welding electrodes, paint pigment, mordants, military smoke preparations.

TABLE II

TITANIUM MINERALS

| *Name* | *Chemical composition* | *Crystal system* |
|---|---|---|
| Rutile | $TiO_2$ | Tetragonal |
| Anatase | $TiO_2$ | Tetragonal |
| Brookite | $TiO_2$ | Orthorhombic |
| Ilmenite | $FeO\ TiO_2$ | Hexagonal, trirhombohedral |
| Perovskite | $CaO\ TiO_2$ | Monoclinic |
| Sphene or Titanite | $CaO\ TiO_2\ SiO_2$ | Monoclinic |

## Occurrence and Production of the Titanium Minerals of Commercial Importance

ILMENITE

The titanium minerals which are of commercial importance are Ilmenite and Rutile. Both are widely distributed, as can be seen in Fig. 1. Ilmenite occurs in three different types of deposit. It is found in beach sand deposits, such as those of Travancore (India), Florida and Senegal. Travancore is currently by far the most important producer of this type, its total output since 1924 having been more than 4 million tons.

At the present time the principal sources of the mineral are great ore-bodies found in several parts of the world. Such deposits exist and are commercially exploited at Sogndal in Southern Norway, in the Adirondacks in New York State, and at Allard Lake in Quebec. This last and most recent discovery is so large that it is

TABLE III

WORLD PRODUCTION IN 1950 OF TITANIUM CONCENTRATES (ILMENITE AND RUTILE) BY COUNTRIES*, IN LONG TONS

| *Country* | *Quantity* |
|---|---|
| ILMENITE | |
| United States | 417,232 |
| India | 212,663 |
| Norway | 103,489 |
| Canada (titanium ore) | 89,732 |
| Malaya | 24,915 |
| Australia | 13,554 |
| Senegal | 776 |
| Spain | 627 |
| Egypt | 256 |
| Portugal | 65 |
| TOTAL | 863,309 |
| RUTILE | |
| Australia | 18,312 |
| United States | 10,704 |
| India | 36 |
| Norway | 31 |
| French Cameroons | 25 |
| TOTAL | 29,108 |

*Figures for the Union of Soviet Republics and China are not available, but titanium minerals are known to exist in Russia.

probable that it will ultimately make North America independent of Indian supply.

A third and smaller source of the mineral arises as a by-product from the magnetic concentration of certain tin ores, such as those of Malaya and, to a lesser extent, of Portugal.

### RUTILE

This mineral is in smaller demand than Ilmenite. Like some of the latter, it is derived, often with other products, from beach sands in Australia (Queensland and New South Wales). It is also available in pebble form in the French Cameroons.

## World Production of Titanium Minerals

In Table III, kindly supplied by Colonial Geological Surveys, Mineral Resources Division, production figures for the titanium minerals of commercial significance for 1950 (the last year for which a substantial number of returns are available), are set out. Although, as has been previously mentioned, only a minute fraction of the annual output of titanium minerals is used in the form of metal, they do in fact contain about a quarter of a million tons of it. It is thus apparent that should there be a demand for titanium alloys for engineering purposes, it is unlikely to be restricted because of a lack of titanium ores for many years.

# PART II

# PRODUCTION OF METALLIC TITANIUM

Although as will have been seen from Table I, the World is by no means poor in titanium minerals, it has to be admitted that at present the metal is rare indeed and well beyond the price that can legitimately be paid for most engineering purposes for which, on the basis of its density, mechanical properties, and relative freedom from corrosion, it might otherwise be advantageously employed. This combination of abundance of raw materials and scarcity of the metal they contain largely arises from that very quality of titanium which so struck Klaproth—its all-too-stubborn reluctance to be reduced to the metallic state.

In the century and a half which has elapsed since Gregor's initial discovery of the element, only two

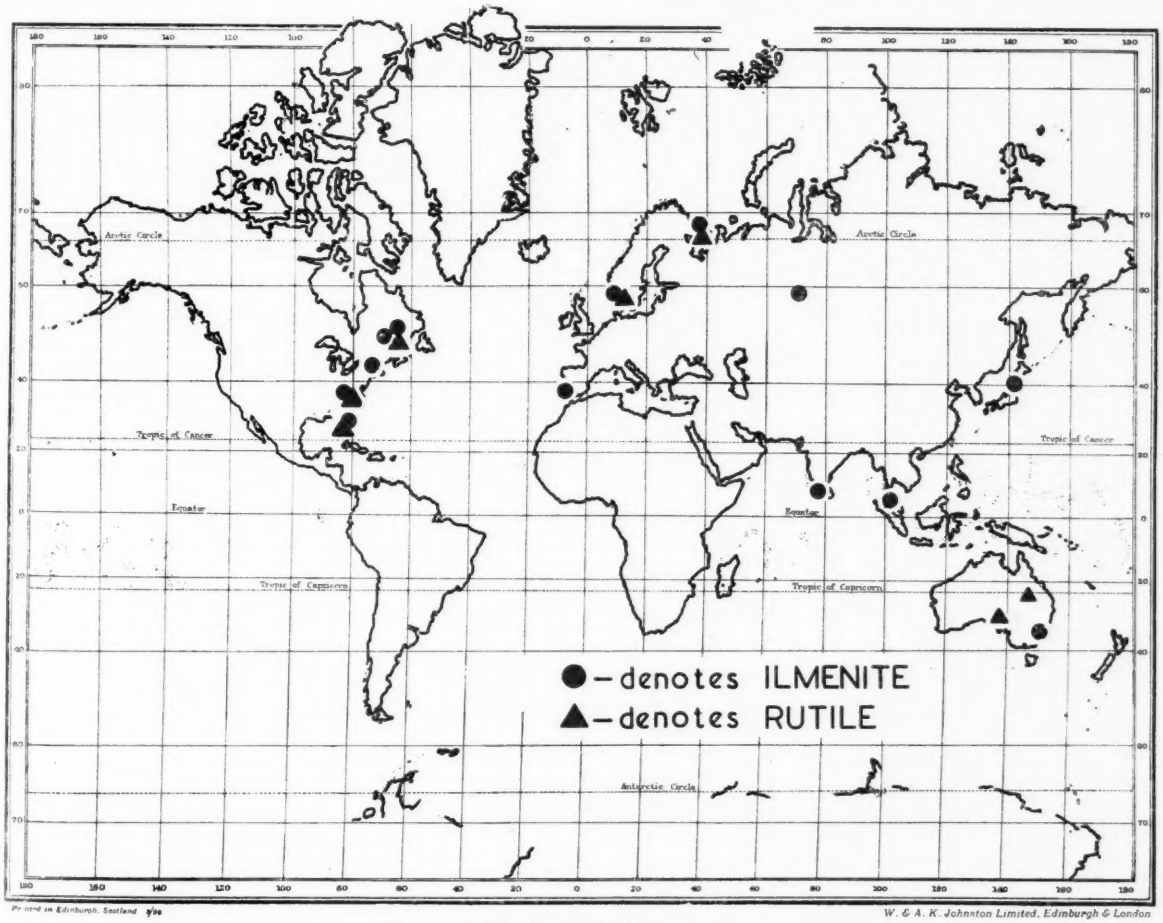


FIGURE 1. Distribution of titanium minerals.

practical processes for its production in *ductile* form, have been evolved. One, the Van Arkel, while yielding the purer end product, is so much more costly in its operation that it seems unlikely that it will be employed except for making metal on a laboratory scale for laboratory purposes. The other, the Kroll, has virtually produced the whole of the titanium so far used for engineering purposes.

## Outline of Production Processes

### VAN ARKEL

This process was developed by Van Arkel, De Boer and Fast[5]. It is essentially a refining process. Crude titanium, made by sodium reduction or some other process, is heated in the presence of iodine. This gives rise to a volatile iodide which is thermally decomposed by coming into contact with an electrically-heated conductor. This can produce a deposit thereon of metallic titanium of high purity*, provided that the material used in the preparation of the iodide is free from certain impurities, such as iron. The process is not, however, considered to be a method readily adaptable for large-scale production. Further, the pure metal comes into being in the form of pencil-shaped rods, which for the manufacture of alloys have to be melted. This, as will be seen later, inevitably introduces impurities.

### KROLL

The Kroll process is extremely simple in conception but its operation on a scale to produce titanium in such quantities as would be of significance to the Aircraft Industry, involves chemical engineering problems of the utmost difficulty and complexity.

Like that of Hunter of thirty years earlier, it consists of reducing titanium tetrachloride by means of a chemically more active metal. While Hunter employed metallic sodium, Kroll used and continues to use magnesium. Both, under the conditions in which they operated their respective methods, were left with titanium in powder form, intermixed with several times its weight of the chloride of the metal used for the reduction of the original titanium salt.

The chemistry of Kroll's process is shown in the following equation:—

$$\underset{\text{Titanium tetrachloride}}{TiCl_4} + \underset{\text{Magnesium}}{2Mg} = \underset{\text{Titanium}}{Ti} + \underset{\text{Magnesium chloride}}{2MgCl_2} \quad . \; . \; (1)$$

Or expressing this differently, 190 parts by weight of titanium tetrachloride, reacting with 48 parts of metallic magnesium, produce 48 of metallic titanium and 190 of magnesium chloride; or put in yet another way—to produce a pound of titanium, theoretically requires a pound of magnesium. In practice, about one and a quarter pounds are employed. This indicates to the engineer that titanium, so long as it is made by this process, cannot be cheap—the present American price of magnesium ingot is 24·5 cents/lb., that of titanium sponge is 500. These figures are impressive rather than satisfactory. Neither magnesium ingot nor titanium sponge are engineering materials. Their relative prices, therefore, are of no real concern to the engineer. At a later stage some comparison is made on a basis involving both cost and mechanical properties of sheets of current titanium, aluminium and magnesium alloys. This puts the price question in better perspective, but in a somewhat worse light.

Before dealing with the intricate techniques which have to be employed to convert titanium sponge into a coherent mass of metal suitable for such metallurgical operations as rolling, drawing, forging, something should be said of the production of titanium tetrachloride.

The chemistry involved is expressed by the following equation:—

$$\underset{\text{Titanium dioxide}}{TiO_2} + \underset{\text{Carbon}}{2C} + \underset{\text{Chlorine}}{2Cl_2} = \underset{\text{Titanium tetrachloride}}{TiCl_4} + \underset{\text{Carbon monoxide}}{2CO} \quad . \; . \; (2)$$

Although this gives the impression of being simple, it is a complex operation, the intricacy of which is broadly indicated by pointing out that while Ilmenite concentrates containing 45 per cent titanium dioxide can be bought for £10 per ton (which is something like £37 a ton for metallic titanium in this form) titanium in the form of pure titanium tetrachloride costs at least £500 a ton of titanium.

The perplexities involved in converting titanium tetrachloride into titanium sponge require some review of the chemistry and physics of both the substances taking part in the reaction, and also of the plant in which this is carried out as a commercial operation.

*Titanium Tetrachloride.* ($TiCl_4$)

This substance, at normal temperature and pressure, is a liquid having the following physical characteristics:

| | |
|---|---|
| Density at 15°C. | 1·76 |
| Melting Point | −25°C. |
| Boiling Point. (At normal pressure) | 136°C. |

It is decomposed by water and by aqueous vapour, which accounts for its use as a material for the production of smoke screens.

*Magnesium*

This metal possesses the following features:—

| | |
|---|---|
| Density at 15°C. | 1·74 |
| Melting Point | 651°C. |
| Boiling Point. (At normal pressure) | 1120°C. |

*Titanium*

This metal has the following characteristics:—

| | |
|---|---|
| Density at 15°C. | 4·5 |
| Melting Point | 1725°C. |
| Boiling Point | Not determined |

*Anhydrous Magnesium Chloride.* ($MgCl_2$)

This substance is extremely hygroscopic. It forms with water, hydrated salts which decompose on heating into magnesia and hydrochloric acid. In its anhydrous form it has the following features:—

| | |
|---|---|
| Density at 15°C. | 2·32 |
| Melting Point | 708°C. |
| Boiling Point | 1412°C. |

*Ti not less than 99·9 per cent.; Si, Fe, Al not more than 0·02 per cent.; $N_2$, Mn and all other elements except $O_2$ not more than 0·01 per cent; C not more than 0·03 per cent.

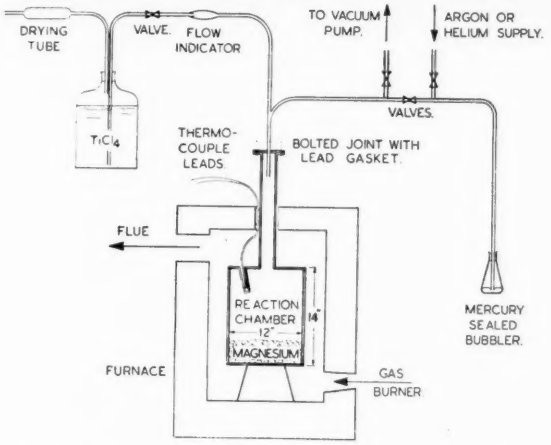


FIGURE 2. Diagrammatic sketch of apparatus used for production of 15 lb. runs of titanium sponge (U.S. Bureau of Mines).

These differences in physical characteristics indicate some of the difficulties which have to be taken into consideration in bringing about the reaction indicated in equation (1). It is, however, the respective chemical properties of the different substances and the extreme sensitivity of titanium to traces of oxygen and nitrogen which make this problem of such formidable dimensions. Both titanium tetrachloride and anhydrous magnesium chloride react with aqueous vapour. Metallic magnesium, if molten, must be out of all contact with oxygen or water vapour. Similarly, since metallic titanium under the conditions of temperature required by the Kroll reaction will combine with all gases except those of the inert series, the decomposition of titanium tetrachloride must be done either under greatly reduced pressure or, in an atmosphere of such completely chemically inert gases as helium or argon.

Figure 2 shows a diagram of the apparatus used by Dean and others[3]. The following is a quotation from U.S. Bureau of Mines Information Circular No. 7381, indicating the manner in which this process was operated in 1946 on something more than a laboratory scale.

"In this size reduction is carried out in an unlined iron pot. The pot, 12 in. in diameter and 14 in. in height, was made from 12 in. pipe with $\frac{3}{8}$ in. plates welded on the ends. The inside surfaces of the pot were carefully cleaned by pickling in dilute HCl (Hydrochloric acid), scraping and finally polishing with an emery cloth. The cover was then welded on and the assembly heated to 500°C. while filled with hydrogen to reduce the oxide formed on the interior surfaces by the welding. After cooling, 20 lb. of carefully cleaned magnesium ingots were introduced through the inlet tube, and the assembly was heated to 150°C., evacuating to a pressure of about 0·005 mm. mercury to remove absorbed gas from the walls of the chamber and the magnesium charge. Tank helium was next introduced, allowing the pressure to build up to slightly above atmospheric, and the temperature raised to about 750°C. The liquid titanium tetrachloride was run into the reaction chamber, slowly at first and then as rapidly as the reaction would permit. A considerable amount of heat was evolved. This evolution of heat was adequate, after the reaction had got under way, to maintain the temperature of the chamber at the desired point without external heating for about two-thirds of the run. In the latter portion of the run, the rate of reaction decreased, reducing the rate at which $TiCl_4$ (Titanium tetrachloride) could be added, and external heating then became necessary. The normal practice was to allow the temperature to rise gradually from an initial value of 750°C. to a final value of 900°C. and to maintain this temperature for about one-half hour after all of the $TiCl_4$ had been added. During the entire run, a slight positive pressure of helium was maintained in the reaction chamber by means of the mercury valve indicated in Fig. 2.

"After the reaction chamber had cooled, it was opened by cutting through the welded joint between the wall and the top of the pot. The charge was removed in the form of chips by a boring operation carried out on a lathe. The greater portion of the magnesium chloride and excess magnesium were then removed from the chips by leaching with cold HCl. The leaching vessel was fitted with an agitator and cooling device, and the reaction chips were added at such a rate that the temperature of the leaching liquor did not exceed 25°C. After the first leaching, the chips were washed, dried, ground to the desired size, given a second leaching in 10 per cent. HCl, and then carefully washed and dried at room temperature.

"The grinding method adopted was wet grinding in a small ball mill, with frequent screening to remove the undersize particles and reduce the proportion of minus 200-mesh material produced. The iron introduced by the grinding was readily removed by magnetic separation along with that picked up while boring the reaction mass out of the chamber."

This quotation shows how complicated was the series of operations which were involved in converting titanium in the form of its tetrachloride into discreet particles of metal, which, without consolidation, would be totally without engineering applications. The next stage is again dealt with by quotation from the same Information Circular.

"The granular metal produced by Dean and associates[3] was satisfactorily consolidated by pressing into compacts at a pressure of 50 tons per sq. in. and sintering for 16 hours at 950° to 1,000°C. in a vacuum of $1 \times 10^{-4}$ mm. mercury. At this pressure, the compression ratio of the powder is about 3·5 : 1. The sintered compacts are ductile, lend themselves readily to cold deformation, and have been made into sheet and bar by specific fabricating methods.

"In another paper, Dean and associates[6] determined the physical properties of titanium metal on $\frac{1}{16}$ in. sheet, using standardized procedures for pressing compacts, sintering, forging and annealing. The Compacts, after pressing at 50 tons per sq. in., were sintered for 16 hours at 1,000°C. in a vacuum of $2 \times 10^{-4}$ mm. of mercury. The sintered compacts

have a density of 4·30, a tensile strength of 83,000 lb. per sq. in., an elongation of 10 per cent., and a Rockwell hardness G 54. They are best worked by cold forging and may be reduced as much as 50 per cent. in thickness in this operation. Compacts were normally forged to 25 per cent. reduction and in this condition have a density of 4·42, a tensile strength of 115,000 lb. per sq. in., 6 per cent. elongation and a hardness of G 81. Physical properties, hardness and microstructure were followed at all stages of the working and also on sheet annealed at temperatures ranging from 400°C. to 1,200°C. Vacuum annealing for 6 hours at 1,000°C. gives a slight increase in density and reduces the strength and hardness to about those of the sintered compact. The forged and annealed compacts were cold-rolled by slight reductions and many passes, with intermediate annealing after 15 to 20 per cent. reduction and finished into sheet with 10 to 60 per cent. reduction."

Table IV gives the mechanical properties of cold-worked and annealed titanium produced by this process, the success of which must, it is felt, have depended on all engaged in the operation possessing, in a marked degree, an almost infinite capacity for taking pains.

Considering this table, and having in mind the large number of batch operations which have had to be carried out to produce metal about 1·6 times the density of current wrought aluminium alloys, but with, in certain respects, less attractive mechanical properties, it may well be felt that what has been done is analogous to the psalmist's evaluation of the parturition of the mountains? But the metamorphosis of the Wrights' machine of 1903 to the Comet of today has required time, expressible in generations, and treasure, astronomically exceeding the ransoms of many kings.

The influence of alloying on the mechanical properties of titanium has yet to be considered and such alloys have to be contrasted with those of other metals over the range of temperature experienced by airframe and engine components.

## Development of the Kroll Process

The description which has been given of the Kroll process of 1946, however great admiration may be for its technical ingenuity, cannot have failed to impress adversely anyone addicted to economic thinking. In its then state of development it was not merely a batch process, but one which involved a number of difficult and different operations, each of which had to be done on a batch basis.

A reaction chamber had to be prepared for each charge. This involved two operations: the chamber had to be closed by means of welding and, after waiting long enough for the contents to cool to atmospheric temperature, the chamber had to be opened by cutting. This led to the loss of the residual heat of both charge and chamber.

The standard way of removing the products of the reaction (roughly one part by volume of titanium sponge intermingled with eight parts of anhydrous magnesium chloride) by boring out with a machine tool, is impressive in its crudity. The chips from this last operation had to be chemically treated in a batch in order to separate the magnesium chloride and leave the titanium as a number of detached particles. These had then to be magnetically treated to remove iron. Finally, the batch application of a powder metallurgy technique involving, *inter alia*, heating this sponge for long hours, at a high temperature, in a high vacuum, had to be employed. This gave rise to metal which had to be forged in order to turn it into an engineering material. Not unnaturally, the elaboration of this many-staged process stimulated a search for a simpler and less energy-consuming method.

TABLE IV

MECHANICAL PROPERTIES OF TITANIUM PRODUCED FROM SINTERED SPONGE MADE BY THE KROLL PROCESS OF ABOUT 1946

| *Property* | | *Cold-worked* | *Annealed* |
|---|---|---|---|
| Density | gm./cc. | 4·5 | |
| Limit of proportionality | tons/in.$^2$ | 32 | 25 |
| Yield stress | tons/in.$^2$ | 45 | 28 |
| Ultimate tensile | tons/in.$^2$ | 56 | 37 |
| Elongation | per cent | 4 | 28 |
| Young's modulus | lb./in.$^2 \times 10^6$ | 15·4 | 16·8 |

The first simplification which has taken place concerns the treatment of the products of the reduction process. Their mechanical boring out and subsequent chemical treatment to remove the anhydrous magnesium chloride, has largely been abandoned. When the reaction is complete and the chamber is about 800°C., time is given for the sponge, anhydrous magnesium chloride and unreacted metallic magnesium, to separate

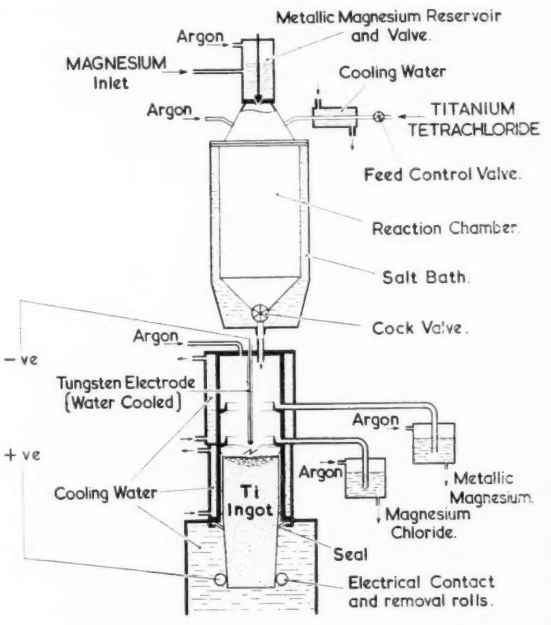


FIGURE 3. Sketch of plant for the continuous production of titanium ingots.

under the influence of gravity. While still fluid, these are tapped off. This done, the contents of the hot chamber, now mainly titanium sponge, are subjected to a high vacuum under the influence of which the remaining magnesium chloride and magnesium are distilled off. Then, as argon is admitted, the chamber is allowed to cool to atmospheric temperature and pressure, when it is opened, the sponge removed and arc- or induction-melted to form ingots.

Probably by such means, the bulk of the titanium now available has been produced, but given enough clever metallurgical engineering, there is no reason to doubt that the Kroll process will cease to be a batch one. Its reaction chamber will be fed in stoichiometric quantities and without intermission with molten magnesium and liquid titanium tetrachloride. It will discharge continuously the products of their reaction into an electric arc furnace in which the freshly created particles of titanium will be melted into a coherent whole. The resulting anhydrous magnesium chloride and any unacted-upon magnesium will be distilled off and condensed. The former will be used for electrolytic re-reduction to the metallic state, while the unacted-upon magnesium will be merely returned to the molten magnesium tank from whence, ultimately, it will go back to the reaction chamber.

Such a scheme as this has been considered by Maddex and Eastwood[7]. Their ideas were sponsored by U.S. Air Material Command, Wright-Patterson Air Force Base, Dayton (Contract No. W33-038, ac-21229). They have largely been tried out and have had such a measure of success as to make reasonably certain that their aim will be reached ultimately. Fig. 2 showed a diagrammatic picture of the Kroll process as it was; Fig. 3 shows what it is on the way to becoming.

Above the reaction chamber is a vessel containing metallic magnesium at a temperature of 760°C., that is at about 110°C. above its melting point. The pressure head in this part of the unit has to be kept constant by the controlled pumping of molten magnesium from a holding furnace, kept at the appropriate temperature. This operation is not novel. For a number of years now the Dow Chemical Company have been transferring liquid magnesium at constant rate by means of mechanical pumps.

From this cistern of liquid magnesium, the metal runs into the rection chamber. Here it meets the titanium tetrachloride. This is fed in at the rate appropriate for the carrying out of the reaction set out in equation (1). The technical requirements of this chamber are such that reaction is complete when the products of it, solid particles of metallic titanium and liquid ones of anhydrous magnesium chloride, reach its conical bottom, from where they flow through a valve to the next part of the unit.

It will be apparent that the dimensions of this reaction chamber are of great importance. They must be closely related to the speed of chemical reaction and to show how difficult it is to give practical effect to this, it should be pointed out that this is influenced both by pressure and temperature. It therefore follows that both these must be kept constant during the operation of the plant. Pressure presents no difficulty; the chamber has merely to be in direct communication with a vessel containing an inert gas, such as argon, which is at an appropriate pressure. Maddex and Eastwood[7] consider this to be 2-3 lb./in.$^2$ above that of the atmosphere. The maintenance of a suitable temperature is more difficult, for the reaction between metallic magnesium and titanium tetrachloride is exothermic, so that the heat liberated within the chamber, and thus the temperature of the chamber itself, depends on the rate of flow of the reagents into it. This must be strictly controlled and, in order to secure as uniform a thermal condition throughout the whole as is possible, Maddex and Eastwood advocate its immersion in a salt bath kept at a *steady* temperature somewhere between 732° and 871°C.

So much for the considerations which determine the dimensions of the reaction chamber. The next portion of the unit is an arc furnace, the design of which presents very great difficulties indeed, for it has to perform a four-fold function. Not only has it to melt the particles of titanium (melting point 1,725°C.) so that they run together and may be subsequently continuously cast into an ingot; it has to distill from the mixture which runs into it from the reaction chamber, the anhydrous magnesium chloride and any unreacted metallic magnesium. These two have to be subsequently and separately condensed and, in liquid form, returned to the appropriate parts of the unit. Thus, this arc furnace is not merely a melting one. It is a continuous casting machine and is also a fractionating still, volatilising and separating two substances, anhydrous magnesium chloride (boiling point 1,412°C. and melting point 708°C.) and metallic magnesium (boiling point 1,120°C. and melting point 651°C.).

To summarise what has been said in this section about this very difficult matter of producing metallic titanium in commercial quantities from its ores—working on batch process lines, the Kroll process has produced substantial quantities of titanium sponge. This, initially by powder metallurgical technique, but later by the technique described and variants involving melting, has been converted into ingots, forgings, sheet, etc. By intensive effort, units are being developed which, while operating on the basis of the Kroll reaction, will do so continuously, producing the metal in the form of ingots, from which wrought products can be, and have been, manufactured. It is not impossible that a continuous process operating on the lines indicated in Fig. 3(*a*) will be evolved in which the input will be almost limited to titanium dioxide, coke and electrical energy. Anyone unfamiliar with metallury, but knowing the mechanical engineering triumphs of the Aircraft Industry may, at this stage, feel that the development of the Kroll process gives promise of titanium becoming available in the near future at a price which would not prohibit its employment for general engineering purposes. The metallurgist, on the other hand, may doubt if this is within the ambit of its potentialities. These facts will be in his mind—to produce a ton of titanium requires a ton and a quarter of metallic magnesium, costing in the United Kingdom

about £400 (and what, as far as the United Kingdom is concerned is more important, consuming about 25,000 kilowatt hours in its manufacture[8]). Further, he will recall that titanium tetrachloride, long an article of commerce, is not yet inexpensive, and, finally, he will hazard that owing to the inherent chemistry and physics of titanium itself, its production in such forms as the engineer may require is likely to be costly in the extreme. These contrasting views will receive further consideration.

The approximate cost per ton of titanium metal in various forms is given in Table V.

TABLE V

APPROXIMATE COST* OF METALLIC TITANIUM PER TON IN VARIOUS FORMS

| *Material* | *Cost in pounds sterling of one ton of titanium* |
|---|---|
| Ilmenite concentrate (45% $TiO_2$) | £37 |
| Titanium tetrachloride | £500-£600 |
| Titanium sponge | £4,000 |
| Bars, hot-rolled | £7,900 |
| Forgings, rounds, discs, etc. | £7,900 |
| Sheet and strip | £11,900 |

*The cost of metallic titanium in this table has been based on current American prices converted on the basis of $2.82/£1 sterling.

## Some Price Considerations

About a century ago, aluminium, now the Aircraft Industry's predominant metal, was sold by the pound at a price equivalent to £125,000 a ton. Today, it can be bought by the thousand tons for £167 a ton, a change brought about by invention and the exploitation of invention, both of which may well make a powerful contribution to the development of a titanium industry.

Whether or not titanium and its alloys are justifiably usable by the aircraft engineer depends on two considerations—what can this metal do which cannot be done by cheaper means, and what is the monetary value of this achievement ?

As this story unfolds, some means of increasing the disposable load of aircraft will be indicated, but what the purchaser is prepared to pay for this must determine the issue.

The military authorities have, rightly, a method of evaluation depending on contemporary exigencies, but this is not so for civil air lines. Through the courtesy of Mr. Peter Masefield, the author is able to give the following figures of gross revenue per annum derived per lb. of disposable load of the following aircraft:—

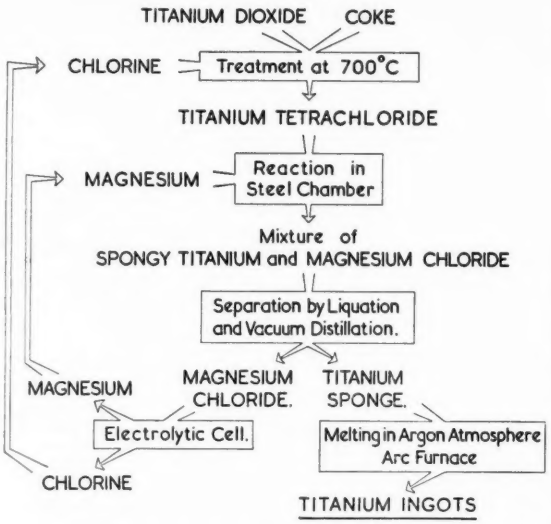


FIGURE 3(*a*). Flow of materials in the manufacture of titanium ingots.

| *Aircraft class* | *Gross revenue in pounds sterling per lb. of disposable load* |
|---|---|
| DC-3 | 12 (actual) |
| Viking (first-class) | 29 (actual) |
| Elizabethan (first-class) | 49 (estimated) |

These figures should be borne in mind when consideration is given to Tables XII and XIII.

Finally, because of two characteristics of titanium, its high melting point (1,725°C.) and its intense chemical activity when molten, its scrap cannot be remelted and used again for making fresh wrought material. While it is to be hoped that this state of affairs will not long endure, for the present, although the metal is initially so costly, there is virtually no rebate to be obtained from the sale of swarf, off-cuts, and so forth.

# PART III

# THE PROPERTIES OF PURE TITANIUM AND OF COMMERCIALLY PURE TITANIUM

## Titanium as an Engineering Material

### PHYSICAL CHARACTERISTICS

Before dealing with those properties of titanium and of its alloys which are likely to be of concern to the engineer, attention is drawn to the physical characteristics of the so-called pure metal, but it should be explained that since, even when made by the iodide process, titanium is not yet produced with a freedom from impurities comparable with that of such metals as tin, lead, zinc, copper, some of the figures given may be only approximations.

On the basis of Table VI it can be said that titanium is virtually a non-magnetic metal of high melting

point, having a coefficient of expansion comparable with that of steel, an electrical conductivity of about 3·2 per cent. that of conductivity grade copper, and a thermal conductivity which is of about the same order. Its density is about 57 per cent. of that of steel and 1·7 times that of aluminium, while its Young's modulus is about half that of iron, and one and a half times that of aluminium.

From the Aircraft Industry's point of view, *at atmospheric temperature* titanium is entirely free from corrosion troubles, for it is attacked neither by air nor natural waters, not excluding sea water. Indeed, such is its resistance in many respects that in chemical engineering it already has application and later may well have wide ones in this field.

Having spoken of the chemical inertness of the metal at atmospheric temperature, an almost paradoxical reverse side of the picture has to be disclosed—in the molten state, titanium is intensely chemically active. It combines violently with all gases other than those of the monatomic series such as helium and argon. This demands that the metal must be melted and cast in an atmosphere of the kind indicated, or else *in vacuo*. Meeting this requirement naturally enough makes such an operation difficult. It does not *per se* make it impossible, but for practical engineering it is, for there is no material, metallic or non-metallic, out of which molds can be made with which liquid titanium (*i.e.* above 1,725°C.) will not react disastrously.

## ENGINEERING CHARACTERISTICS

The foregoing brief description does not contain much to attract and it omits much of significance. Except for the metal's elasticity, density and, at atmospheric temperature, chemical inactivity, no qualities have been mentioned which are of particular interest either to the aircraft structural or mechanical engineer. Both would doubtless like to know of those properties which are their more practical concern, but here a difficulty presents itself—the influence of very small quantities of foreign matter makes a very considerable difference to the mechanical properties of the metal. The amount and nature of these impurities depend largely on the process by which the titanium is produced and on that by which it is finally melted. This is borne out by the results in Table VII.

TABLE VI

PHYSICAL CHARACTERISTICS OF PURE TITANIUM, *i.e.* BETTER THAN 99·9 PER CENT. Ti.

| | |
|---|---|
| Atomic number | 22 |
| Atomic weight | 47·9 |
| Crystalline structure: | |
| Up to 885°C. | Close-packed-hexagonal |
| Above 885°C. | Body-centred-cubic |
| Atomic spacing: | |
| Up to 885°C. | $a = 2{\cdot}950$ A° |
| | $c = 4{\cdot}683$ A° |
| Above 885°C. | $a = 3{\cdot}31$ A° |
| | $c = 3{\cdot}31$ A° |
| Coefficient of linear expansion | $15-730$°C., $8{\cdot}8-9{\cdot}2\times10^{-6}$ per °C. |
| Thermal conductivity | 0·036 calories/cm.²/cm./sec./°C. |
| Specific heat | 0·13 |
| Electrical resistance, microhm/cm./cm.² | 60 |
| Density gm./c.c. | 4·507 |
| Melting point | 1,725°C. |
| Young's modulus, lb./in.² | $15\times10^6$ |

TABLE VII

THE INFLUENCE OF METHOD OF MANUFACTURE ON THE MECHANICAL PROPERTIES OF ANNEALED "COMMERCIALLY PURE" TITANIUM

| *Property* | *Method of production* | | | |
|---|---|---|---|---|
| | *Van Arkel* (1) | *Kroll with powder technique* (2) | *Kroll with induction melting* (3) | *Kroll with metal electrode arc melting* (4) |
| 0·2 per cent. proof stress (tons/in.²) | 6·8 | 28·6 | 32·2 | 28·2 |
| Ultimate stress (tons/in.²) | 15·6 | 35·3 | 35·8 | 33·5 |
| Elongation, per cent. | 55 | 25 | 25 | 29 |
| Hardness, Brinell | 57 | 185 | 228 | — |

While, from the engineering point of view, titanium cannot be melted without undergoing some change in chemical composition and therefore in mechanical properties, on the laboratory scale this is not necessarily the case. In common with some other metals and in amounts which so far have not exceeded 600 grammes, it can be melted by electromagnetic levitation[22]. This can be done *in vacuo* or in an atmosphere composed of one of the inert gases.

TABLE VIII

MECHANICAL PROPERTIES OF COMMERCIALLY PURE TITANIUM

| *Property* | |
|---|---|
| 0·2 per cent. proof stress | 33·5 tons/in.² |
| Ultimate tensile stress | 39·0 tons/in.² |
| Elongation | 23 per cent. |

Up to the present time more "commercially pure" titanium has been produced and used for engineering purposes than has been the case with its alloys, so the characteristics of the former will be considered first.

In the form of annealed sheet, strip, bars, forgings and so on, the commercially pure titanium can now be expected to have at least the mechanical properties given in Table VIII.

This metal would cost approximately the following prices:—

| | |
|---|---|
| Sheet, strip | £11,900 per ton |
| Bars, forgings, etc. | £7,900 per ton |

The combination of the mechanical properties and the price which has to be paid for them, prompts examination of their relative significance in practical engineering terms.

## Relative Cost of a Titanium Tension Member

No agreed standard of comparison for structural materials exists, nor can a satisfactory one be proposed. If, however, the case of a tension member made in sheet or strip is considered, this does do something towards what is required. The weight of such a tie depends on the load it has to support, its length, cross section, density and working stress. If such a member were designed in the following materials:—

Commercial Grade Titanium (Annealed),
Aluminium Alloy 75S, and
Magnesium Alloy FS1,

on the basis that in each case the working stress should be the same proportion of the 0·2 per cent. Proof Stress, then on the assumption that the latter is:—

| | | |
|---|---|---|
| Commercial Grade Titanium | 33·5 | tons/in.$^2$ |
| Aluminium Alloy 75S | 29·5 | ,, |
| Magnesium Alloy FS1 | 16·5 | ,, |

then the densities being:—

| | | |
|---|---|---|
| Commercial Grade Titanium | 0·16 | lb./in.$^3$ |
| Aluminium Alloy 75S | 0·101 | ,, |
| Magnesium Alloy FS1 | 0·064 | ,, |

the relative weight of ties designed on this basis would be:—

| | |
|---|---|
| Commercial Grade Titanium | 1·39 |
| Aluminium Alloy 75S | 1·00 |
| Magnesium Alloy FS1 | 1·13 |

and the respective cost of the *material in them*, on the basis of current American prices converted at $2·82 to £1, being:—

| | | | |
|---|---|---|---|
| Commercial Grade Titanium | 106·4 | shillings | /lb. |
| Aluminium Alloy 75S | 3·4 | ,, | ,, |
| Magnesium Alloy FS1 | 7·4 | ,, | ,, |

their relative costs would be:—

| | |
|---|---|
| Commercial Grade Titanium | 43·5 |
| Aluminium Alloy 75S | 1·0 |
| Magnesium Alloy FS1 | 2·5 |

These figures are unsatisfactory in many ways. They take no account of the respective costs of fabrication. They relate to the simplest type of structural member at atmospheric temperature. Further, the titanium is regarded as being of commercial grade and in the annealed condition. As will be seen later, by cold work and by alloying, a substantial improvement in the mechanical properties of the material can be made, but this will not be of such a character as to make the cost of a tension member approximate to that of one made in the light alloy aircraft structural alloys.

## Members Which Depend on Rigidity

Since so many physical considerations are involved in the design of struts and beams, no comparison comparable with the one for a tension member can be made. However, on the rigidity/weight basis, titanium and titanium alloys at atmospheric temperature have a somewhat lower specific rigidity than the older structural alloys.

While the elastic moduli of titanium can be appreciably raised by alloying (admittedly at the sacrifice of some desirable qualities), it appears improbable, even with a reduction in price, that the metal will be extensively used for the main structure of even high speed aircraft. This view was recently endorsed by Sir Ben Lockspeiser[9].

TABLE IX

SPECIFIC RIGIDITY OF FOUR AIRCRAFT MATERIALS

| *Material* | *Young's modulus lb./in.$^2$/10$^{-6}$* | *Specific gravity* | *Specific rigidity 10$^{-6}$* |
|---|---|---|---|
| Commercial grade titanium (annealed) | 15 | 4·5 | 3·3 |
| Aluminium alloy 75S | 10 | 2·9 | 3·5 |
| Magnesium alloy FS1 | 6·5 | 1·8 | 3·6 |
| Nickel chromium steel, B.S., S.99 | 29 | 7·8 | 3·7 |

## Forgings

The airframes of contemporary machines are not without some massive forgings. Some are made in alloy steel, but more are of such aluminium alloys as D.T.D.364 and 683. Since, in general, their form is such that questions of rigidity do not arise, it is the 0·1 per cent. Proof Stress of the material which will provide the design criterion. On the basis of this and of current prices for forging bars made of the three selected alloys, the figures in Table X give the relative price of the material in the forgings.

As has been previously said, comparisons of the type made in Table X should not be valued above their true worth; they reveal but one part of a many-sided story. The design criterion adopted is not wholly sound. All considerations as to the preparation of the materials for forging, their forging, subsequent machining and heat treatment have been neglected. Such omissions might well, and in fact sometimes do, eliminate the apparent two-to-one advantage shown in the favour of nickel-chromium steel. They cannot, however, unfavourably influence the nearly fifty-eight-to-one superiority of the ferrous alloy over commercial grade titanium, for the cost of the processes in the relation to the latter not taken into consideration, greatly transcends that of their application to the older materials.

Allowing for the very grave defects in the accuracy of the yardstick, crudely constructed to measure the relative value of commercial titanium as a material for airframe forgings, one fact emerges clearly—at the present stage of its development it is not attractive.

TABLE X

RELATIVE COST OF THE MATERIAL IN FORGINGS OF EQUAL STRENGTH MADE IN THREE AIRCRAFT ALLOYS

| *Material* | *0·1 per cent. proof stress tons/in.$^2$* | *Density in lb./in.$^2$* | *Cost/lb. shillings* | *Relative cost* |
|---|---|---|---|---|
| Commercial grade titanium | 32 | 0·16 | 70·5 | 57·7 |
| Aluminium alloy D.T.D.683 | 27 | 0·101 | 3·3 | 2·0 |
| Nickel chromium steel, B.S. S.99 | 70 | 0·283 | 1·5 | 1·0 |

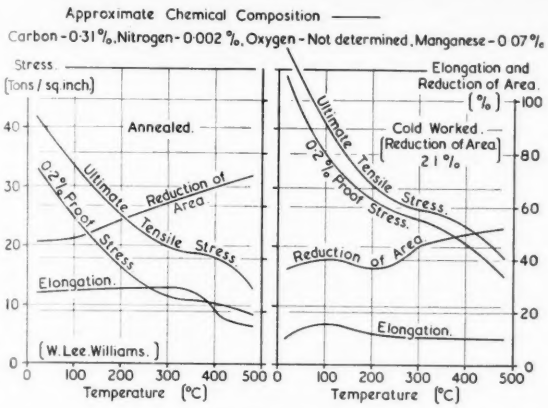


FIGURE 4. Tensile properties at elevated temperatures of arc-melted commercial purity titanium.

What is not so clear is whether, given the great price reduction which, it is hoped, may be on the way, it would be technically suitable. The metal belongs to the hexagonal system and therefore it would be expected to have mechanical properties varying with the direction in which they are measured; more evidence is required on this point before one can be sure that even were titanium cheap, it would also be useful for the purpose under consideration. Given a satisfactory answer to this last doubt and bearing in mind that the specific 0·1 per cent. Proof Stress of the three materials contrasted in this section is:—

| | |
|---|---|
| Commercial Titanium | 7·1 |
| Aluminium Alloy D.T.D.683 | 9·3 |
| Nickel Chromium Steel, S.99 | 9·0 |

it can well be imagined, as will be demonstrated later, that a titanium *alloy* might, if judged on this basis, go to the top of the class.

## Some General Observations on Commercially Pure Titanium

What has been said in this section has been written for the benefit of the airframe designer in relation to commercially pure titanium which, from the strictly scientific point of view, is not pure titanium at all, but an alloy containing mainly carbon, iron, oxygen and nitrogen and generally 99 to 99·5 per cent. Ti.

Nothing has been revealed about this so-called commercially pure titanium which indicates that, under present conditions, it has any commercially justified applications in the airframes of present aircraft. For two reasons at least, however, it must not be swept aside. Certain possible uses have so far received no consideration and no attempt whatever has been made to evaluate the metal's potentialities—it is at the beginning of its metallurgical career. Very pure iron, be it remembered, has an ultimate tensile stress of well under 20 tons per square inch[10], while a number of alloy steels of reasonable ductility, containing over 95 per cent. of iron, have more than five times the strength of the pure metal.

There are at least four ways in which commercially pure titanium might well be employed with technical, if not with certain economic, advantage. The author believes that metal with about the mechanical properties given in Table VIII could be employed in the form of rivets, closeable by cold heading and with, partly as a result of cold work, a pin shear ultimate as high as 35 tons per square inch. Experiments in America, with this object in view, have not as yet succeeded, but their measure of ill-success has not been such as to eliminate hope.

While not yet an article of commerce, titanium tubing with a 0·2 per cent. Proof Stress of about 33 tons/in.$^2$ and an elongation of over 20 per cent. has been made. If it can be manufactured with the uniformity of quality required for aircraft hydraulic and pneumatic services, there would certainly appear to be a field of application in this sphere, for its Specific Proof and Ultimate Stresses are markedly better than those of such alloys as D.T.D.310, 328, 503 and T.26.

As a fireproof bulkhead, commercial titanium can replace stainless steel with a saving in weight for equal thicknesses of 37 per cent. If the oxygen content does not exceed 0·15 per cent, that of the nitrogen 0·05 per cent. and that of the carbon 0·15 per cent., the metal is readily welded by means of an argon arc technique, which may simplify the making of the bulkhead. Further, since the thermal conductivity of titanium is almost the same as that of stainless steel, there is no detracting disadvantage.

Nothing has yet been said about the use of commercial grade metal in the airframes of supersonic aircraft. This omission is intentional. Somewhat surprisingly in view of its high melting point, unalloyed *annealed* titanium has disappointing creep characteristics, even at room temperature[11] [21]. Fig. 4, based on work by Lee Williams[12], shows the variation with temperature of annealed and cold-worked material as regards its static mechanical properties. The creep properties of the cold-worked metal, however, are much better than those it possesses in the annealed state.

Finally, in military aircraft, there is reason to suppose that the grade of titanium under consideration may prove effective as armour, on a weight basis, for it can be surface-hardened by a number of methods which have yet to be tested realistically.

The metallurgical potentialities of the metal depend largely on alloying.

# PART IV

# ALLOYS OF TITANIUM

While the previous section of this paper has shown that titanium of commercial purity, regardless of its present price, has few very obvious applications in the airframe of a subsonic aircraft, or in that of a supersonic one, or in the power plants of either, a guarded optimism was expressed about the potentialities of its alloys. The

full exploration and exploitation of these alloys, it is insisted, is yet to be—further alloy births are a probability. Three thousand years have elapsed between the making of the first steel knife and the manufacture of the first rustless one, while between the earliest bronze blade and the latest "Nimonic" one, the period of gestation has been some 2,000 years longer. Titanium alloys as yet have the defects of youth. Time is in their favour.

## Alloys With Metals

From a consideration of relative inter-atomic distances, it would be anticipated that the metal would form a solid solution with each of those of Group 1B and of Groups V-VIII of the Periodic Table. This means that it is metallurgically likely that a binary alloy could be made with each of the following:—

Copper, silver, gold, vanadium, niobium, tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt, and nickel.

Experiments, some as early as 1936 if not before[13], have shown that with all these, and certain other elements, alloys can be made. The qualities of many have not yet been fully explored, so it may well be that some have not been correctly evaluated. Fig. 5[14] indicates the influence of varying amounts of the different elements on the ultimate tensile stress and elongation of the titanium to which it has been added. Most of these produce increases in strength, some indeed of notable magnitude but, with the single exception of silver, all cause decreases, some startling, in elongation. This very limited information, however, changes the picture of the engineering possibilities of titanium from the drab and sombre to one pregnant with possibilities of engineering significance. Further experiment has shown that the simultaneous additions of two or more of some of the metals listed can give desirable increases of static strength, with less serious reduction in ductility than when a single alloying constituent is employed.

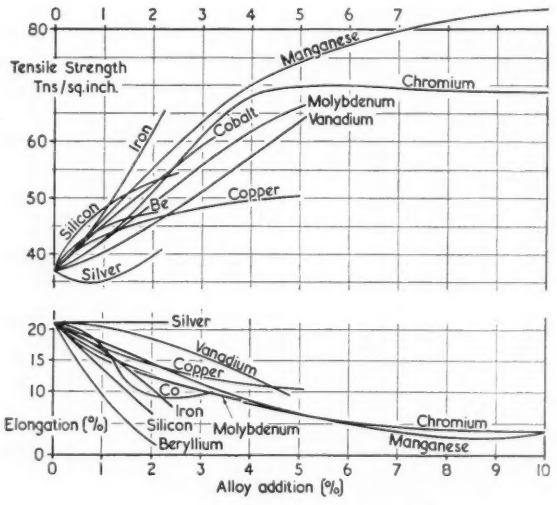


FIGURE 5. Effect of alloying additions on the tensile properties of binary titanium alloys.

## Alloys With Gaseous Elements

Titanium possesses to an outstanding degree the ability to form solid solutions with oxygen, nitrogen and hydrogen and, surprising as it may seem, extremely small quantities of two of these gases, oxygen and nitrogen, have a marked influence on the strength of the metal in which they are dissolved. This is clearly shown in Fig. 6, in which the amount of dissolved gas is shown, for the sake of convenience, as an atomic percentage. If, however, this is converted into a weight percentage, the significance of the gases is even more impressive—this can be done approximately, in the case of oxygen, by multiplying the atomic percentage by 0·34, the nitrogen one by 0·30, and that of hydrogen by 0·021.

The question may well be asked: "How can these gases be got into the metal?" In the case of oxygen the most usual mechanism is by diffusion. Jenkins and Worner[15], give an account of how they prepared titanium-oxygen alloys containing up to more than 5 atomic per cent. of the gas. They used a piece of thin strip made of iodide titanium having the following determined impurities:—

| | |
|---|---|
| Oxygen | 0·02 per cent. by weight, *i.e.* 0·06 atomic per cent. |
| Nitrogen | 0·03 per cent. by weight |
| Iron | 0·02 ,, ,, ,, ,, |
| Tin | Strong trace |
| Antimony | ,, ,, |
| Copper | Faint ,, |
| Silicon | ,, ,, |
| Vanadium | ,, ,, |
| Magnesium | ,, ,, |
| Manganese | ,, ,, |

The strip was heated in *air* for several minutes in the range 500°-750°C. This produced an adherent film of titanium oxide, the thickness of which depended on the length of the heating period. The strip was then heated at 850°-950°C. *in vacuo*, for 30 hours. This technique produced throughout the metal a uniform diffusion of the original surface film and thus enabled the authors to prepare a number of specimens on which the graph in Fig. 7 has been based. Before leaving this point one further comment should be made—the initial heating in air at 500°-750°C. did not introduce any appreciable increase in the nitrogen content of the metal.

Finally, when considering the titanium-oxygen alloys it should be mentioned that at temperatures above 1,150°C. there is evidence that the oxygen content of the alloy begins to decrease and as a consequence, after heating at such a temperature, the room temperature mechanical properties will be different from those which the alloy possessed before heating.

Similarly, nitrogen can be introduced into titanium by heating in an atmosphere of the gas at about 800°C. and subsequently *in vacuo*, to allow uniform diffusion. While, as was seen in Fig. 6, nitrogen on a weight basis is a more powerful strengthening addition to titanium than oxygen, with alloys of equal hardness the cold-working properties of the alloy produced by oxygen additions are better than those of the alloy made by nitrogen ones.

Hydrogen can get into titanium in a number of ways, such as by acid pickling, heating above about 350°C. in an atmosphere containing free hydrogen, or hydrogen containing gaseous compounds, including aqueous vapour. It does not appear to perform a useful function, but it can easily be got rid of by soaking *in vacuo* at a temperature of 800°C. for a period which will depend on the thickness of the section.

## Alloys With Non-metallic Solids

Most non-metallic solids alloy with titanium forming limited solid solutions and/or compounds. Information in this field is limited. In the case of carbon there appears to be enough evidence to indicate that up to

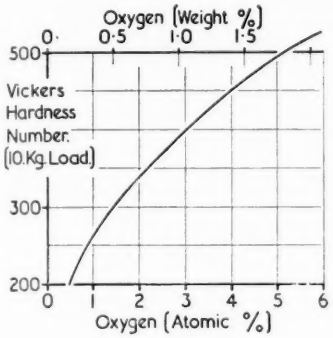


FIGURE 7. Hardness/oxygen concentration relationship for annealed titanium-oxygen alloys.

0·2 per cent. it goes into solid solution in the metal, increasing its tensile strength but reducing its ductility. Above this amount, and up to about one to one and a quarter per cent., carbon is present in titanium as a finely disseminated carbide. In this form it has little influence on the static mechanical properties, but as regards impact resistance, fatigue and notch fatigue, there is insufficient satisfactory evidence. With regard to welding, however, carbon in excess of 0·15 per cent. is regarded as undesirable. As can be seen from Fig. 5, titanium alloys with the metalloid silicon, giving rise to results which are not attractive.

## Available Alloys

By means of certain metallic and/or non-metallic additions, it is clear that a vast number of titanium alloys can be made. Evidence of varying degrees of reliability is available on some of the characteristics of those which have been made. Table XI sets out the nominal chemical compositions and some room temperature mechanical properties of such alloys as can be regarded at present as being commercially obtainable at a price from about once and a half, to twice, that of the pure commercial metal in the same form.

Since the mechanical properties disclosed in Table XI, as far as proof and ultimate stresses are concerned, are superior to those of all steels used for aircraft forgings with the exception of S.99, it is at once apparent that, bearing in mind the respective specific gravities of the ferrous and titanium alloys, the latter give scope for weight economy in the production of forged parts.

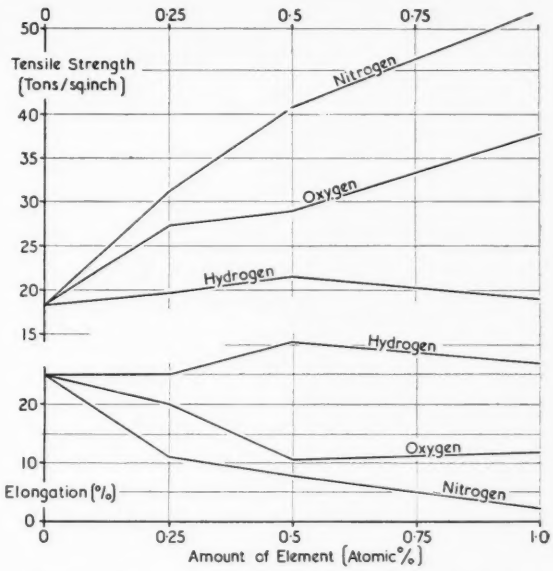


FIGURE 6. Effect of additions of gaseous elements on the tensile properties of iodide titanium.

Experience so far has shown this to be true but, as will be seen, this has been saved at a monetary cost which may be thought to be prohibitive in civil and even in military aircraft.

TABLE XI

TYPICAL CHEMICAL COMPOSITION AND ROOM TEMPERATURE MECHANICAL PROPERTIES OF SOME COMMERCIALLY AVAILABLE TITANIUM ALLOYS
(*See also* Appendix I)

| *Constituents other than* Ti | *Condition* | *0·2 per cent. proof stress tons/in.²* | *Ultimate stress tons/in.²* | *Elongation per cent.* |
|---|---|---|---|---|
| 0·2 Fe, 0·02 $N_2$, 0·1 $O_2$ | Annealed sheet, bar, forgings | 34 | 39 | 23 |
| As above | ½ hard sheet | 42 | 49 | 12 |
| 1·8 Cr, 0·9 Fe, 0·15 $O_2$, 0·04 $N_2$, 0·03 C | Annealed sheet and strip | 36 | 56 | 19 |
| 2·0 Cr, 2·0 Fe, 0·15 $O_2$, 0·04 $N_2$, 0·06 C | Annealed sheet, bar, forgings | 56 | 62 | 14 |
| 7 Mn | Sheet | 58 | 63 | 14 |
| 4 Mn, 4 Al | Annealed bar, forgings | 60 | 65 | 18 |
| 2·0 Fe, 2·0 Cr, 2·0 Mo, 0·2 $O_2$, 0·1 $N_2$, 0·05 C | Annealed sheet, bar and forgings | 56 | 63 | 13 |
| 2·7 Cr, 1·3 Fe, 0·25 $O_2$, 0·02 $N_2$, 0·05 C | As above | 58 | 67* | 16* |
| 5·0 Cr, 3 Al, 0·5 C | As above | 68 | 74 | 10 |

*Depending on grain size and heat treatment, properties ranging from 90 tons/in.² tensile and 6 per sent. elongation down to 60 tons/in.² tensile and 30 per cent. elongation can be obtained.

In Table XII[17] a comparison is made between the costs of the same forged part, made in the American alloy steel 8630, and the titanium forging alloy containing 4 per cent. aluminium and 4 per cent. manganese (RC 130B).

The figure of £80 is sufficiently startling to require confirmation. This is available in Table XIII, taken from a paper by Hanink[18], in which cost per lb. of weight saved is given for a number of gas turbine items.

These tables illustrate the very high and varying price which has to be paid in order to save weight. This is attributable to four causes, one of which is current inexperience in the forging and machining of the new material. Table XII shows that at present, the relative costs of a particular titanium alloy part in comparison with an alloy steel one are:—

| | |
|---|---|
| Material | 41 times as much as the steel |
| Forging | 40 " " " " " " |
| Machining | 17 " " " " " " |

## Forging

While forging costs, like those of every other manipulative process, will come down as experience is gained, the fundamental qualities of the metal prevent the adoption of the simplest techniques. As mentioned already, titanium, when hot, not only combines with oxygen, nitrogen and hydrogen (whether elemental or not), but this metal/gas alloy film slowly diffuses through the basic matrix, profoundly altering its mechanical properties. Further, there is another objection to the presence of this coating—in drop stamping it interferes greatly with the flow of the metal in the die.

Naturally, the presence of scale being objectionable, steps have to be taken to reduce its formation to a minimum. The heating of the forging stock therefore demands the exercise of care as regards the chemical composition of the atmosphere of the furnace, the rate of heating and also, the maximum temperature of the stock. From the film, or scale, point of view this last should be low. On the other hand, when forging, the lower the temperature the greater the difficulty in inducing the metal to flow without cracking.

Faced with this dilemma the practical man has compromised. He has fixed on a range of 880°-980°C. In this temperature zone, the stock is deformed with more difficulty than would be experienced in forging alloy steel, therefore heavy and consequently expensive plant is desirable. Finally, subsequent to forging a prolonged anneal at 650°-700°C. is beneficial. A warning should, however, be given that some of the two phase alloys, even after such a treatment, are unstable and subsequently undergo embrittlement if used at temperatures in the range 250°-450°C.

While these facts indicate the use of the lowest possible practical temperature for forging, there is an additional reason for avoiding high temperatures. With the titanium alloys now used for forgings (mainly 2·7 Cr, 1·3 Fe, 0·25 $O_2$, etc.) grain growth takes place rapidly at high temperatures. This will influence adversely the subsequent room temperature properties of the alloy as regards ductility, impact resistance and fatigue. Finally,

TABLE XII

RELATIVE COST ANALYSIS—TANK SUPPORT FITTING[17]

*(Conversion of dollar costs has been made at the rate of $2.82 to £1 sterling)*

| *Item* | 8630 *Steel* | *Titanium alloy RC 130 B* |
|---|---|---|
| Weight of rough forging ... ... | 23·5 lb. | 13·8 lb. |
| Material cost ... ... ... ... | £2·13 | £87·0 |
| Forging ... ... ... ... | 0·67 | 27·0 |
| Machining ... ... ... ... | 20·60 | 355·0 |
| Total cost of finished part ... ... | £23·40 | £470·0 |
| Weight saved ... ... ... ... | — | 5·9 lb. |
| COST/LB. WEIGHT SAVED ... ... | — | £80 |

as mentioned previously, above 1,150°C. the oxygen content of those alloys whose mechanical properties depend on the presence of this gas within the material tends to decrease, with consequent subsequent decrease in static mechanical properties at room temperature.

Table XIII emphasises how important, yet varying, is the influence of machining on the cost of an item. With a simple form such as a rotor disc, the price differential between steel and titanium alloy is relatively low, but with a part of greater complexity, such as a turbine support, the gap broadens markedly. Two observations have to be made about the significance of these two tables. The figures recorded are based, not on theory or on what is often even more misleading, salesmen's talk; they are the result of actual experiment by intelligent people well versed in the manufacturing techniques normally employed for the making of such parts in the conventional materials. The cost figures for these processes in relation to the titanium alloy arise from the use of established techniques applied to a material with which experience is almost non-existent. Almost certainly both forging and machining costs will be greatly reduced but, at the present state of the art, at least in relation to the machining costs, there are wide differences of opinion among those with such experience as exists, as to the best ways of doing this.

The machining of titanium and of titanium alloy can be compared with that of an 18 : 8 austenitic steel, but it is much more costly. A sales organisation not unusually addicted to the saying of acceptable things, has stated that, on the average, the machining of

TABLE XIII

COST AND WEIGHT ANALYSIS OF STEEL AND TITANIUM ALLOY GAS TURBINE PARTS

| *Item* | *Material and approximate weight of finished part in steel and in titanium alloy in lb.* | | *Approximate cost of weight saving per lb.* |
|---|---|---|---|
| Compressor rotor disc | Steel AMS 6342 | 25·0 | |
| | Titanium alloy | 14·0 | £21 |
| Compressor stator blade | Steel AMS 5613 | 0·06 | |
| | Titanium alloy | 0·04 | £62 |
| Turbine support | Steel AMS 6322 | 3·0 | |
| | Titanium alloy | 2·0 | £69 |
| Compressor rotor blade | Steel AMS 5613 | 0·10 | |
| | Titanium alloy | 0·06 | £84 |

titanium alloys costs about 3½ times more than that of austenitic steel. At present no machine shop foreman would fail to imply that this was a considerable understatement.

## Additional Properties

A somewhat superficial examination of the titanium alloys has now been made. On the basis of the mechanical properties in Table XI, possibilities of weight saving are suggested. In those applications in which the design criterion is specific proof stress (as can be the case with some massive forgings), reductions in weight would seem to be obtainable, provided that an alloy having a proof stress in excess of 45 tons/in.$^2$ is selected.

In view of this possibility, the airframe and engine designer will wish to have further particulars as to such mechanical properties as fatigue, notch fatigue, impact, creep, damping, etc. Before dealing with these, two general observations of significance have to be made.

## A Serious Defect

Titanium and the present titanium alloys have quite deplorable rubbing properties. The metal is inclined to pick up on any other on which it is rubbing. At least for the present, this cold welding tendency debars the use of the alloy for shafts unless these have a sleeve to provide a rubbing surface in the journals, or ball or roller races are fitted. A titanium internal combustion engine piston, attractive though it seems from several points of view, is extremely unlikely to be successful for the present. It is even doubtful if a titanium alloy nut can be satisfactorily used in connection with a bolt of similar composition.

At this stage the engineer may feel that the shadowy case for the use of titanium alloys which has been disclosed has now been destroyed by the last admission. There may be grounds for pessimism, but the author looks upon this difficulty as likely to be of a temporary nature. Titanium and its alloys can be given a hard surface by means of anodising. If such a coating will not stop galling, or has too ephemeral an existence, then gas case-hardening produced by heating either in oxygen or nitrogen can be employed. Failing this, a hard surface can be produced by carburising. These are matters for experiment, and the experiments are in hand. Under conditions in which questions of contact corrosion are unlikely to arise, a flash coat of copper may be obtained by dipping in a copper cyanide bath. This may prevent "pick-up." Finally, a chemical treatment, giving rise to an adherent film can be used satisfactorily in conjunction with molybdenum disulphide, subsequently used as a solid lubricant.

## Fatigue

Measured as fatigue generally has been, and still often is, measured, namely by the application of cyclic stresses to highly polished specimens in the form of fixed rotating beams, or as ties or columns, titanium and its alloys made by *fusion* methods have excellent fatigue properties.

Unlike practically all the metals of the non-ferrous group, titanium has a true fatigue limit. Results obtained with the types of test-pieces enumerated show, as is always the case in fatigue determinations, considerable scatter, but it is undoubtedly true to say that the ratio of the fatigue resistance of the metal and of its alloys to their respective tensile strengths exceeds, and sometimes greatly exceeds, one half. Thus the fatigue resistance of this group, in the form of the very unrealistic test-pieces already mentioned, is better than that of alloy steels.

When, however, notched fatigue test-pieces are used, this is no longer the case. Hanink[18], using test-pieces with and without a severe notch, found that while the notched to unnotched endurance ratio for his alloy steel specimens, tested under the same conditions, was 15 per cent. for identical titanium ones made of the 2·7 Cr, 1·3 Fe, 0·25 $O_2$ alloy, this figure was only one fifth this amount. An *S*/*N* curve of the Remington Arms Company[20], in tests with a less severe notch (stress concentration factor 2·7) employing the commercially pure alloy showed the $10^7$ cycle endurance to be over 50 per cent. of that of the unnotched specimens.

These disturbing results have received confirmation from other experiments but the position is not entirely without hope. It does seem possible that by control of initial grain size and by close attention to metallographic structure, better resistance may be obtainable when titanium alloys are subjected to tri-axial cyclic stresses. Nevertheless, at present, it has to be admitted that the notched fatigue endurance of such strong titanium alloys as have been tested is poor to very poor.

One further point should be mentioned about the fatigue characteristics of the alloys. Hanink[18] states that the application to them of the well-known Almen shot-peening technique does not improve, but considerably reduces their fatigue limit. While his careful experiments support this contention, it is possible that an improvement may be obtained by a modification of the peening technique. This view is based on the behaviour of magnesium (also a hexagonal metal) for, when shot-peening was first applied to its alloys, their fatigue resistance was definitely lowered thereby. Now, however, by a modification of the method, Found[19] has demonstrated that his system of peening does in fact raise their fatigue resistance.

## Impact Resistance

Because of the variety of methods which have so far been used for the production of titanium, considerable differences have existed in the properties of alloys of the same chemical composition. These differences are probably more marked in relation to notched bar impact resistance than with any other quality.

So far, the influence of trace elements, grain size and heat treatment, all very potent in relation to the impact resistance of the ordinary engineering materials, have received insufficient study in the case of the titanium alloys. It is known that, like the ferritic steels, they are extremely sensitive to temperature. At 300°-400°C. an izod impact value of 100 ft. lb. or more can be obtained. At such a temperature the fracture would be ductile, but

at a lower one, which would certainly be above room temperature, it would be wholly brittle. This change in the type of fracture is accompanied by a sharp decrease in impact resistance, but at room temperature, it is probable that the strong titanium alloys, when their chemical compositions and methods of manufacture have become standardised, will possess notched bar impact values better than those of the current strong wrought aluminium alloys used in airframe structures. These values are likely to be comparable with those of the stronger alloy steels.

## Welding

It has been mentioned that commercially pure titanium can be readily argon or heli-arc welded, but nothing has yet been said on the use of this method for joining the strong alloys. Before doing this, one point must be made as to welding the commercial grade metal, for it has a practical significance and may, on occasion, limit the use of the method.

From time to time, emphasis has been placed on the absorption of oxygen and nitrogen when the metal is above about 800°C. When its gas content rises, so does its strength, but on the other hand its ductility decreases. It is because of this that the inert gas type of welding gives the best results. If, however, a weld as strong and as ductile as the parent metal is required, contact of oxygen and nitrogen with the molten and neighbouring hot titanium must be prevented. The standard welding torch does this on the working face, but when welding sheet or plate, an inert gas atmosphere must be provided over the hot area on the reverse side of the job.

The position from the metallurgical point of view on the welding of the strong alloys is too complicated to explain in the course of a review of this type, but a lucid description of the present state of the art can be obtained from a recent paper by Voldrich[16].

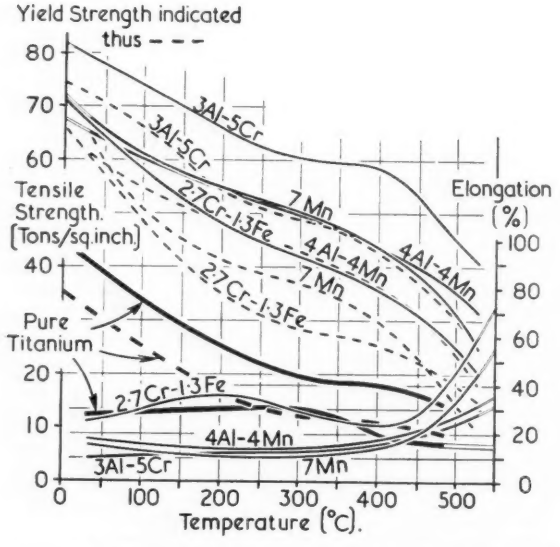


FIGURE 8. Effect of temperature on the tensile properties of titanium and titanium alloys.

Roughly speaking all titanium alloys can be argon or heli-arc welded, but while with those which have what the metallurgist terms a two-phase structure, the tensile strength will be satisfactory, ductility will be generally extremely low. This may be increased in some cases by subsequent heat treatment.

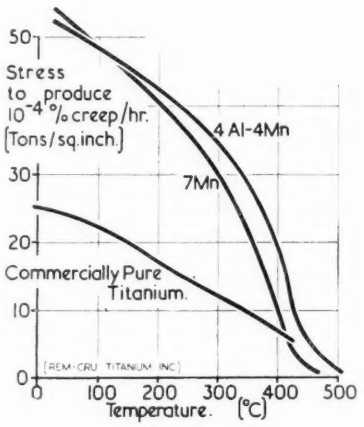


FIGURE 9. Influence of temperature on creep of titanium and titanium alloys.

Brown[17], at present exceptionally, contends that welds made in two-phase titanium alloys by flash welding possess good ductility. This technique is particularly adapted to repetition work and might well find aircraft engine applications.

Should there be a demand for a weldable sheet with a 0·2 per cent. proof stress of 40 tons/in.², a tensile of about 60 tons/in.², combined with an elongation of not less than 15 per cent., this is a metallurgical possibility.

## Properties at Elevated Temperatures

The influence of increase in temperature on the mechanical properties of commercially pure titanium is indicated in Fig. 4. The point was made that, in spite of the high melting point of the metal, it was, whether in the annealed or cold-worked conditions, embarrassingly temperature conscious. Fig. 8 gives similar information for both the annealed commercially pure titanium and the titanium alloys. This shows that the metallurgist has succeeded in raising stress levels to a gratifying degree. On the other hand, it indicates that his success in reducing the temperature sensivity of his creations has been somewhat limited. Admittedly it is impossible to make any firm pronouncement as to what temperature limitation is imposed on the use of these alloys, for this must be varied by the nature of their employment, but, in the light of Fig. 8, it would not seem unreasonable to hazard a guess that, except for short term uses, about 350°C. constitutes the upper limit of their employment.

## Creep

This aspect of titanium and of the titanium alloys is of more interest to the engine designer than to the structure engineer unless the latter is concerned with vehicles having a speed considerably in excess of that

of sound. Some figures are available, but it should be emphasised that creep results are difficult to reproduce. Both grain size and very slight variations in chemical composition have considerable influence on the rate of alloys to the same specification. This well-justified warning having been uttered, attention is drawn to Figs. 9 and 10.

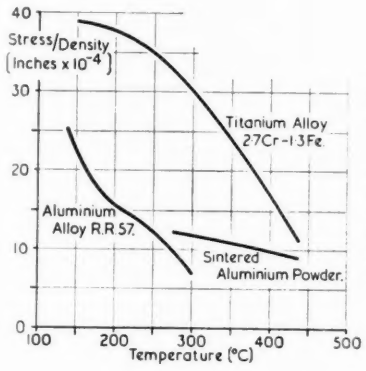


FIGURE 10. Comparison of materials for axial compressor blades.

Variation in specific stress with temperature required to produce 0·1 per cent. total creep strain in 100 hrs.

In Fig. 9 the superior resistance to creep of two titanium alloys to that of the commercially pure metal is shown. Once again the temperature sensitivity of the three materials is emphasised. In Fig. 10, derived from a paper by Lockspeiser[9], relative specific creep rates of three materials used for axial compressor blades are shown. While at all temperatures within the range of the experiment the titanium alloy containing 2·7 per cent. chromium and 1·3 per cent. iron is very superior to the other two, the downward slope of its specific creep curve is impressive—on the basis of the considerable body of evidence available, the upper limit of temperature above which neither titanium nor its alloys can be usefully employed, is, contrary to earlier expectations, of modest height.

## PART V

## SUMMARY

To give to the aircraft industry a precise evaluation of a metal whose technical and economic potentialities are, at the best, ill-defined and, at the worst, no more than the subject of conjecture, is impossible. On the other hand, by analogy with the development of other engineering metals, surmises can be made. Some, at least, of those so made will, it is hoped, not turn out to be unjustified.

The author, not wholly unacquainted with metallurgical history, contends that emphasis should be laid not on our knowledge of this Cinderella of the engineering metals, but on our ignorance of it. The Iron Age has lasted at least 3,000 years, and the current annual world production of iron and steel is some 200,000,000 tons. Yet not a year, in fact not a month passes, but some new discovery is made in relation to the production of this ancient metal, its properties or those of its alloys.

With these facts in mind, it is but necessary to set down the story of titanium in the same terms. It has been known, but known be it emphasised only to a very limited few, for just a little over a century and a half. In the whole of this period less than 1,000 tons of it have been produced[17], and this production has been largely limited to the past four years. Surely this alone excuses ignorance. Further, if one adds that not a generation has passed since the making of the first titanium alloy and bearing in mind present achievements, then, surely, one can truly say—"of this metal we as yet know little, but on the basis of this little, we expect much."

This tempered optimism is founded on these facts:—

1. Ores of the metal are widely distributed and even with our present knowledge, it can be said they contain a vast quantity of it.
2. Its extraction is based on a process which, although extremely costly, is not much more than a decade old. There is therefore by analogy with the histories of such ancient engineering metals as iron and copper, and with such new ones as nickel, aluminium and magnesium, a hope and indeed more than a hope, that new and more economic means of production will be found.
3. The present physical, mechanical and fabrication characteristics of *commercially pure* titanium are such that, neglecting price considerations, the aeronautical engineer, whether concerned with airframes or power plants, cannot fail to be interested and indeed to indulge in a certain hopefulness for, in some applications, it is definitely superior to austenitic steels.
4. The number of known titanium alloys having, at least up to 350°C., some specific properties superior to those of ferritic alloy steels, is considerable and the probabilities of further developments in this field are also considerable.
5. The temperature above which it is not considered advisable to use the strongest structural wrought age-hardening aluminium alloys being about 100°C., titanium ones would appear to have a field of usefulness from this temperature until they in turn are beaten by more heat-resisting materials.
6. The metal and its alloys at present possess at least some of the following unattractive features—low specific Young's modulus, physical instability at slightly elevated temperatures, poor rubbing properties, chemical activity about 500°C., difficulties in forging, heat treating, machining and fabrication. These, if past experience is a guide, are likely to be mitigated in varying degrees, some by better understanding and others by discovery of new or improved techniques. It is, however, probably the improvement of the elastic moduli by an amount sufficient to attract the designer of supersonic aircraft which will be the problem of the greatest intractability.

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## Appendix I.

CHEMICAL COMPOSITION OF AMERICAN TITANIUM AND TITANIUM ALLOYS

| *Designation* | *Producer* | *Nominal composition per cent* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *C* | *O* | *N* | *Al* | *Cr* | *Fe* | *Mn* | *V* | *Mo* | *W* |
| Commercial Titanium | | | | | | | | | | | |
| Ti-55 A | Titanium Metals | 0·02 max | Trace | 0·02 | — | — | 0·10 | — | — | — | 0·02 max |
| Ti-75 A | Titanium Metals | 0·02 max | Trace | 0·02 | — | — | 0·10 | — | — | — | 0·02 max |
| RC-55 | Rem-Cru | 0·2 max | (*a*) | (*a*) | — | — | (*a*) | — | — | — | — |
| MST Grade III | Mallory-Sharon | 0·25 max | — | — | — | — | — | — | — | — | — |
| RC-70 | Rem-Cru | 0·2 max | (*a*) | (*a*) | — | — | (*a*) | — | — | — | — |
| MST Grade IV | Mallory-Sharon | 0·3-0·8 | — | — | — | — | — | — | — | — | — |
| Ti-100 A | Titanium Metals | 0·02 max | Trace | Trace | — | — | 0·1 | — | — | — | 0·02 max |
| Titanium Alloys | | | | | | | | | | | |
| Aluminium-Iron Alloy MST 2 Al-2 Fe | Mallory-Sharon | 0·5 | — | — | 2 | — | 2 | — | — | — | — |
| Aluminium-Manganese Alloy RC-130 B | Rem-Cru | 0·2 max | (*a*) | (*a*) | 4 | — | (*a*) | 4 | — | — | — |
| Chromium-Aluminium Alloy MST 3 Al-5 Cr | Mallory-Sharon | 0·5 | — | — | 3 | 5 | — | — | — | — | — |
| Iron-Chromium-Molybdenum Ti-140 A | Titanium Metals | 0·05 | 0·20 | 0·10 | — | 2·0 | 2·0 | — | — | 2·0 | — |
| Chromium-Iron-Aluminium Ti-150 A | Titanium Metals | 0·02 | 0·25 | 0·02 | — | 2·7 | 1·3 | — | — | — | 0·02 max |
| Iron-Vanadium Alloy MST 2·5 Fe-2·5 V | Mallory-Sharon | 0·5 | — | — | — | — | 2.5 | — | 2·5 | — | — |
| Manganese Alloy RC-130 A | Rem-Cru | 0·2 max | (*a*) | (*a*) | — | — | (*a*) | 7 | — | — | — |

(*a*) Few hundredths to few tenths.

COMMERCIAL FORMS IN WHICH THE METAL AND ITS ALLOYS ARE AVAILABLE

| *Designation* | *Sheet* | *Strip* | *Plate* | *Wire* | *Bars* | *Rod* | *Forging Billets* | *Forgings* | *Welded Tubing* |
|---|---|---|---|---|---|---|---|---|---|
| Commercial Titanium | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Titanium Alloys* MST 2 Al-2 Fe | √ | √ | | | √ | | √ | √ | |
| RC-130 B | | | | | √ | | √ | √ | |
| MST 3 Al-5 Cr | | | | | √ | | √ | √ | |
| Ti-140 A | √ | √ | √ | √ | √ | | | √ | |
| Ti-150 A | | | | | √ | | √ | √ | |
| MST 2·5 Fe-2·5 V | √ | √ | | | √ | | √ | √ | |
| RC-130 A | √ | | | | | | | | |

*See composition table.

## Discussion

SIR ARTHUR SMOUT (Director, Imperial Chemical Industries Ltd.): He congratulated Major Teed on a brilliant survey of the position in regard to titanium and on the objective way in which he had approached the subject, in contrast to the over-glamourised versions and ballyhoo from which they had suffered in so many directions. Indeed, in the endeavour to free his survey from exaggeration, it seemed that Major Teed had barely done justice to the new metal. Things moved so fast and so far that it was difficult for anyone to keep abreast of the latest developments, particularly for those who were not in hourly contact with the problems.

It was to be regretted that the author had not exhibited specimens illustrating titanium "from ore to finished product." That could have been arranged and would have added much to the value of the lecture; but presumably he was not anxious to trespass on the exhibition which, it was understood, was being staged by the Chemical Society a few weeks hence.

Titanium had been spoken of as "*The* metal of the future," but he preferred to call it "*A* metal with a future."

Although titanium sponge was difficult and costly to produce, because of its stubborn reluctance to be reduced to a metallic state—and also because it was so chemically reactive in the molten condition—they must not assume that today's high prices were representative of those three or five years hence. The author had recalled that, a hundred years ago, aluminium was a chemical curiosity costing £125,000 per ton. Titanium was not quite at that figure yet! Sixty years ago the world production of aluminium was a mere 750 tons; but the production of titanium, in the few years during which the metallurgists had become attracted by its properties, had already surpassed that figure. The world production of aluminium today was of the order of 1,850,000 tons a year. He did not know if anyone were bold enough to forecast the rate of production of titanium sixty years hence, but it might well rise as dramatically as had aluminium over a similar period.

He believed that the difficulties to which the author had rightly called attention were capable of solution, and, indeed, were on the way to solution; therefore, they were temporary in character. In that connection he recalled how the engineer had shied off aluminium and the light alloys thirty years ago because of the difficulties of fabrication, difficulties commensurate with those they were experiencing today with titanium. Therefore, they should keep these difficulties in perspective.

He did not think that there was any revolutionary process covering the extraction of titanium just around the corner, either in this country or in the United States, but a vastly improved process, which involved not only lower capital investment, but a lower cost of production, was, at the moment, in the development stage in this country. In that respect they were ahead of the United States. It was ready for application to production on a scale which might well meet the United Kingdom's needs over the next few years.

In Fig. 2 the apparatus used in the United States for the production of titanium sponge in 15 lb. lots in 1946 had been shown and he appreciated that Major Teed would not claim that to be typical of today; today titanium was being produced in the United Kingdom in batches of half a ton, and titanium cast ingots were being made on a production scale weighing 180 lb. each.

He did not despair of the chances of scrap recovery and when a method became effective it would reduce costs dramatically.

Argon, which was essential to the process, cost in this country today 1s. per cu. ft., but it could be obtained as a by-product, if the demand justified the capital outlay, for 2d. per cu. ft. The process was all worked out awaiting the demand.

The problems connected with titanium production at all stages—for nothing would hold the stuff when it was molten—were very difficult, but they were worthy of the attention of the best brains in the field of metallurgy. In this country at the present time there were teams of men who were not only gifted, but who were also full of

initiative, enterprise, courage and enthusiasm, already tackling the problems; it was also important to know that they did not lack the funds commensurate with the magnitude of their task.

While he had great faith in the future of titanium, its development involved tremendous courage and enterprise and money. If there were any who thought they would be able to obtain titanium at cost plus 6/8 per cent., he hoped they would think again, for if they were thinking in that way the United Kingdom would still be paying tribute to the United States in regard to titanium for the next 25 years and, what was worse, they would suffer, both in quantity and quality of the material. They must not imagine that titanium could be produced in a back yard on a small scale at cost plus 6/8 per cent. It was a major enterprise.

DR. N. P. ALLEN (Superintendent, Metallurgy Division, National Physical Laboratory): He was particularly pleased to learn from Sir Arthur Smout of his new process and hoped that before very long they would have samples of the products to examine.

He believed that the continuous process for making titanium, as illustrated by Major Teed, had never actually operated on a large scale and that the processes now being used for the production of titanium in larger quantities were still essentially batch processes.

The real difficulty with the continuous process for titanium production was in the mechanical properties of the reaction mass, formed when titanium tetrachloride and magnesium were introduced to each other; the mass, consisting of titanium particles and liquid magnesium chloride, had the consistency of a very stiff toffee and would stick to anything. There was real difficulty in transferring it from one reaction vessel to another.

Major Teed had perhaps been a little pessimistic about the cost of working up titanium from the sponge to the finished product. The figures which had been given represented the price of the operations plus the price of experience; but the price of experience had to be paid once only, and there was no doubt that the operating costs would come down rapidly with time.

At the N.P.L. it had been found that the best quality commercially-produced titanium passed through the machine shops without giving rise to any particular comment. Those machine shops were accustomed to dealing with rather unusual materials, but, on the other hand, experimental titanium alloys were often difficult, and frequently needed to be ground.

The alloys made today were mostly somewhat impure and contained quantities of oxygen, hydrogen and nitrogen, which made a difference to their properties. That was particularly important in relation to notch sensitivity, of which the high-strength alloys were at present suspect. It would be noted that the alloy which had been withdrawn, and which contained 3 per cent. chromium and $1\frac{1}{2}$ per cent. iron, was rich in oxygen; but it was withdrawn on account of notch sensitivity in fatigue and the difficulty of ensuring regular properties.

It was noticeable that in America, when they wanted to make an alloy of exceptional toughness, they chose to make it from a sponge having the lowest possible hardness figure. The normal output had hardness values after being melted from 140 up to a little over 200 Vickers; a hardness much above 200 Vickers was not acceptable. The average hardness was said to be about 165 Vickers. When alloys of the highest toughness were required they chose a special sponge having a Vickers hardness of less than 140, perhaps somewhere about 120. The lower toughness obtained in alloys made with harder sponge was due very largely to the proportions of oxygen and nitrogen in the sponge. The way in which they reacted upon the quality of a high tensile alloy was perhaps rather easy to understand, although he did not think the reason for it was fully appreciated. The high strength alloys were composed of mixtures of two forms of titanium, *i.e.* the $\alpha$ form, which was stable at room temperature, and the $\beta$ form, which was stable at high temperatures. The solubility of oxygen in the $\alpha$ constituent was very much higher than in the $\beta$; if an alloy containing (say) 0·3 per cent. of oxygen were produced in such a form that it contained a little $\alpha$ and a lot of $\beta$, it was possible that the $\alpha$ constituents would contain as much as one per cent. oxygen and would be very brittle. It was the lack of control over the distribution of oxygen between $\alpha$ and $\beta$ which was probably responsible for lack of reproducibility of high tensile titnanium alloys.

At present most of the alloys contained iron, chromium, manganese and a small amount of aluminium. It was interesting to note what little use had been made of the alloys containing aluminium alone. Aluminium was lighter than titanium, and it was quite inconceivable that the titanium-aluminium alloys were not examined almost as soon as titanium was produced. Nevertheless, they had not been developed, and aluminium was used in conjunction with some other element which was a $\beta$ former. The reason was probably that in the very early days the sponge was relatively impure, and the alloys in which aluminium was present had proved unworkable.

In recent American publications it was stated that the titanium-aluminium alloys were exceptional in their welding properties and also in their strength at high temperatures. There were signs of a tendency to revert to simple aluminium-titanium alloys. If that were correct, great advantage was to be expected. Major Teed had said that the real weakness of titanium from the point of view of aeronautical engineers was the low ratio of the modulus to the density. By the addition of aluminium the density could be lowered appreciably and the ratio be much improved.

Alloys of low density and high elasticity to density ratio would be very useful if they could be worked satisfactorily, and detailed attention should be given to the working properties of this type of material.

PROFESSOR A. J. MURPHY (The University, Birmingham): Titanium was suffering from telescoped history. What had happened to aluminium in the course of a hundred years had been made to happen for titanium in six or seven years. The development of titanium had had to await the perfecting of the technique of high

temperature vacuum melting of metals; once that step was taken, it was possible to see what were the properties of approximately pure titanium and of some of its alloys. It was only within the past few years that anybody could say with confidence that commercially pure titanium was even a ductile metal.

He was glad that Major Teed had said that he was nearer to the optimist than to the pessimist; it would be a great pity if the Aircraft Industry were discouraged from taking very seriously indeed the possibilities of the use of titanium. Three years ago the Inter-Services Metallurgical Research Council had expressed their unqualified view that titanium was of the greatest importance to the Services in this country, and the Council had not departed from that standpoint since.

Fig. A (*above*) showed some stampings which had been made in Birmingham with titanium alloy, using dies which were in current use for forging strong aluminium alloys. They were made without any particular difficulty. Fig. B (*below*) showed that the flash could be clipped satisfactorily from the stampings with the ordinary tools used for strong aluminium alloys.

He could say without hesitation that the forging of strong titanium alloys today presented less difficulty than did the forging of Y alloy 25 to 30 years ago.

The stampings illustrated were of material containing about 2·5 per cent. chromium, 1·3 per cent. iron and about 0·2 per cent. oxygen. The 0·1 per cent. proof stress was in all cases more than 60 tons/in.$^2$, the tensile strength was in all cases more than 72 tons/in.$^2$ and the elongation was 9-11 per cent.

There were in this country people who could make the metal and those who could make the stampings; in view of the properties he had indicated, and the other feature which Major Teed had not emphasised, namely, the superb resistance to corrosion, it would be difficult to over-rate the significance of titanium to the Aircraft Industry.

G. L. BAILEY (British Non-Ferrous Metals Research Association): The pessimistic school in respect of titanium, to which at one time that evening he began to think Major Teed belonged, had arisen as the result of the reaction from the extraordinarily foolish enthusiasm of many people in the early days. It was thought then that titanium was to be the wonder metal. But three things went wrong: there was then no hope of obtaining the material more cheaply, the creep properties at elevated temperatures were not so good as had been thought, and the Young's modulus was low.

He thought that the difficulty of preserving a proper sense of proportion in the matter ought not to be so great as sometimes it appeared. Sir Arthur Smout had already referred to a hopeful development on the production side. But perhaps the mechanical properties had not been put in their best perspective, because a lot of work was going on which had not yet by any means reached finality, and it was hoped that there would be improvement in a number of respects.

A real difficulty was to determine how much effort should be put into the work, because an immense amount remained to be done. He did not think there was any evidence that the difficulty of the disappointingly low creep resistance of titanium at really high temperatures would be overcome, and he felt that they must accept the fact that titanium as they knew it at present was not likely to be a lot of use as a stress carrier at temperatures above 500°C. But he considered there was a lot of hope that it would be used at temperatures below 500°C., as indicated by results put forward so far. There were alloys in development which he was sure would be better for compressor blades than that to which Professor Murphy had referred.

Again there was hope of improvement with Young's modulus. Whether or not it would be good enough they did not know.

One of the real difficulties to which he did not see a solution at present was that of re-melting scrap. Any material from the ingot to the finished article produced quite a lot of process scrap. If that material were contaminated by surface oxidation in the course of fabrication so that they could not re-melt it without producing an inferior product, the difficulty became real, and it must be overcome if the price were to be kept to the sort of figure for which they hoped.

In the next few years there would be a lot of developments, and until they had seen some of them they should not rule out the possibility of the use of titanium.

S. B. BAILEY (*Associate Fellow*): Major Teed had presented a paper which gave what was perhaps the reaction of the typical airframe structural engineer to titanium. Aeronautical engineers had been intrigued by the latent possibilities in titanium alloys; they had probably been shocked by the price of those alloys, but they might perhaps derive some comfort from the fact

that they were less than one-fiftieth the price of gold and were much more useful.

Except in one field, that of supersonic guided missiles, where the superior specific strength of titanium alloys as compared with aluminium alloys at medium temperatures might be essential, all that the structural people could hope to get from titanium alloys was the direct saving in weight which their higher specific strength offered. He did not think Major Teed had fully brought out how very much more important the titanium alloys would be to the power plant engineer.

In the axial flow compressor of an aircraft gas turbine, where frontal area was of extreme importance, the blades would always tend to be long and the drum diameters small; the drum stresses arising from centrifugal force on the blades would be high. At the high pressure end of the compressor, where steel blades had to be used at present, the change to titanium alloys would save 40 per cent. of the blade weight even if the change were only one of direct substitution of one metal for the other. But titanium alloy blades could be thinner at the roots than steel blades because of the reduced centrifugal loading, and therefore the blade weights might be expected to be reduced by rather more than 50 per cent. With a reduction of that order in the loads imposed by the blades, a much lighter drum could be used. A pound of titanium alloy used to replace two pounds of steel in the compressor blades might save much more than its own weight in the drum, where the centrifugal field might be too small to justify using titanium; Hanink had quoted a figure of five pounds of engine weight saved through the use of one pound of titanium alloy in the compressor rotor blades.

As a result of those effects of dynamic loading, there was a much stronger case for using titanium alloys in aircraft gas turbines than in airframe structures. The case was strengthened by the ability to use thinner blade sections near the roots, which would improve the compressor efficiency at a given rotational speed, giving an increase in engine power or jet thrust, as the case might be, and an improved specific fuel consumption. Those who were pessimistic about the future of titanium in aeronautics might reduce their pessimism by a factor of six if they would look more at the power plant and less at the airframe.

He was rather puzzled as to why the author, when considering the economics of titanium alloys in civil aircraft, had quoted Mr. Masefield's figures for gross annual revenue per pound of disposable load. If the tare weight of an aircraft were reduced by $X$ pounds through using titanium alloys in the engines there would be an extra $X$ pounds available for the disposable load. But a large part of that disposable load was fuel, which had to be carried anyway. He suggested that the material figures were the annual revenues per pound of *payload*, and those were the figures which should be quoted; they would, of course, be much higher than those given at the end of Part II of the paper. When multiplied by the factor of five or six, which he had mentioned, and by the service life of the aircraft, there would be no difficulty in justifying the employment of a material like titanium for compressor blades, even if the cost of the finished blades were one hundred times the cost of the forged bar from which they were produced.

In war-time military aviation, provided that the raw materials and electric power were available, man hours were a better guide than cost to the practicability of using titanium alloys in aircraft construction. Reference had been made to the cost of machining titanium and its alloys. The chief reason why some materials were very much more expensive than others to machine and grind was that those processes applied to the difficult materials occupied a longer time. The production problem with axial flow compressor blades was already acute when aluminium alloys and steel were used. Lest it became intolerable when titanium alloys were adopted, it was important that research on new methods of machining those alloys be given every bit as much support as research on new methods of extracting the metal. There would be little advantage in having titanium available by the ton at an economic price if they could not fabricate it quickly enough to use it when engines were required by the thousand and blades by the million.

G. R. EDWARDS (Vickers-Armstrongs, Ltd., *Fellow*): He had been impressed by the bursts of eloquence in connection with making the metal in the first instance and by the fact that very few people had said what they were to do with it when it was made. He daresay that titanium would be used in aeroplanes. There was always the incentive of using a material because a competitor was using it. He felt that through the ages that was the consideration which had made people use something they did not want to use; they had found that they had no alternative.

It had relieved him a little when he had gathered from Sir Arthur Smout that the Americans had not got anything on them in respect of titanium either! He had felt greatly relieved to hear also from Sir Arthur that there was no problem of finance that was controlling the production of titanium in this country.

SIR ARTHUR SMOUT remarked that he was talking of research.

MR. EDWARDS: He believed it would be honest to say that the "balloney"—and it was something which happened in this country too—about titanium did not originate from the people who had to use it. He had had discussions in America with people who were using titanium. In the first instance they had said that they felt there was no future at all for it in subsonic aeroplanes except in places which became hot. They had agreed with Major Teed that things such as bulkheads were likely places where it might be used with advantage, and he had seen an American military aircraft having titanium actually built into it in that particular application. But they had said that they were divided on the matter. Some had said they thought it would be of great value in supersonic aeroplanes, and he knew of one case where a considerable amount of titanium was built into such an aeroplane or was

projected to be built into it. There was another school in the United States which said that that was not the right answer, but that a rather extravagant use of light alloys was a better way than to use titanium.

American manufacturers were making determined efforts to overcome the fabricating problems in making pieces to go into aeroplanes, because the trouble with titanium did not end when they had made the ingot or the strip. There was quite a lot of know-how associated with the forming of titanium, particularly from sheet. He was assured by the people concerned that difficult though it was, they were confident that the difficulties would be overcome. They put them in the same category as the difficulties in the machining of D.T.D. 683.

Judging from what he believed to be their considered view, he was inclined to say that his friend and colleague, Philip Teed, had again got himself into the position he was in quite often, and that was, the right one. He was on the optimistic side of the centre line, and it was a good place to be. The Aircraft Industry in this country should follow the advice of Mr. G. L. Bailey, keeping a watchful eye on the whole business, but not being led astray by a too optimistic assessment of the position.

G. FORREST (Aluminium Laboratories Limited): After reading the paper, he had referred to Hanink's published results (to which the lecturer referred*) and had found that this investigator, using a notch giving an elastic stress concentration factor which could not be much greater than about 8, had obtained a corresponding "reduction of fatigue" factor of 18. He pointed out that, if in a material the reduction of fatigue due to a notch was by a very much greater factor than that corresponding to elastic stress concentration, the position was very serious. He had no doubt that, in this particular case, there was a quite logical explanation, but he hoped that further work would be done before too generalised conclusions were drawn from these tests.

He was a little doubtful anyway about the use of notch sensitivity values in arriving at a general assessment of materials, because, although laboratory fatigue tests might show very great differences between one material and another, when in fact components were considered on which the changes of section were on a large scale, he believed—or he had believed, until he had seen the results he mentioned—that all materials gave a notch sensitivity factor approaching one.

SIR ROY FEDDEN (*Fellow*): He was glad to propose a vote of thanks to the lecturer, particularly because he liked to regard Major Teed as an old friend, having known him for pretty well 25 years. From time to time during the period between the wars he had visited Weybridge to discuss aircraft matters with the Vicker's Company and on those occasions he had always looked forward to a talk with Major Teed, for such talks were stimulating.

He looked upon Major Teed's sojourn in America as Scientific Adviser to the Ministry of Aircraft Production during the 1939-45 War as among the best work he had done; he did an excellent job for this country and for the Allies during the three or four years he was over there. Every sort of problem and conundrum was set him by people over here, and very seldom did he fail to get some answer out of our Allies at a time when it was not always easy to do so. But in addition to his duties as Scientific Adviser he felt that he had done even greater work as an ambassador and spreader of goodwill between this country and the United States; he had this great gift, which was not given to many technicians.

On the introduction and the time of development of new materials, he recalled that when he was a pupil apprentice at a motor car factory he had worked on a gearbox and dashboard in aluminium for the car of the managing director of the firm. It had involved what in those days was thought to be an outstanding effort, and he had been very proud to take part in this work because aluminium was a rare commodity in the early years of this century. When Brearley had evolved stainless steel at the end of the First World War, even members of his own firm had thought it an interesting but rather freakish development, and that there was no future for it commercially because it would cost too much money to produce. The Aircraft Industry had never yet been beaten by a new material or process if it held out a big enough prize to win, and therefore he did not feel very worried about the eventual future use of titanium, if it could be proved to be worth while.

Some 20-25 years ago, when they had not such a clear picture before them as now of the relative merit of stiffness and strength of an aircraft structure, he had heard in that same lecture hall such men as Frank Barnwell, Green, Pierson, North, Leslie Acheson and others arguing about the comparative advantages of high tensile steel and aluminium for aircraft construction. The solution of this problem had all come out in the wash; and so he believed it would be with titanium.

DR. H. SUTTON (Ministry of Supply, *Fellow*), *contributed*: In view of the special features of titanium and its alloys of interest and potential importance for aircraft, aero-engines and equipment it was very appropriate to have a paper on this "new" metal by an experienced aircraft engineer with a wide knowledge of aircraft materials and their limitations.

Major Teed had very fittingly referred to the work of Kroll, whose early work in Europe and further work in the United States has given them a process for making titanium which worked and had yielded titanium at a time when no other known process could have been used so effectively. Major Teed had also referred to the work of quite a number of specialist research workers and their work, making a very suitable selection and had mentioned work done in many countries. It was perhaps appropriate that they should all recognise and acknowledge the enormous effort that had been put into titanium research and development in the United States and the considerable achievements in technical fields that had resulted.

*HANINK, H. H. (1952). Application of Titanium to Aircraft Engines. S.A.E. National Aeronautic Meeting, New York, 21st April 1952.

On the economics of use of titanium alloys in aircraft, was not the really important matter that of the capital value of weight saving per pound or other weight unit of titanium or, in a military aircraft, the increase of range, load capacity or performance available, in relation to the increased cost due to the use of titanium? If some hundreds of pounds weight could be saved on each engine and 5 to 10 per cent. of the weight of the airframe, as seemed to be achievable by use of titanium or titanium alloys in applications where stainless or other steels would normally be used, there did indeed seem to be strong hopes of worth while gain in both commercial and military fields.

The combination of physical and mechanical properties of titanium alloys had been stated by several aircraft engineers to be particularly favourable to resistance to distortion and weakening by skin-heating in very fast aircraft during flight at low altitudes. Did Major Teed's views differ on that point?

The comparisons for members made in commercial titanium stressed in tension and otherwise, as given by Major Teed were very interesting. Some of the present alloys, however, showed properties at raised temperatures up to 400°C which placed them in more favourable perspective for use in 'heat zones.' In view of the extreme youth of titanium alloys and progressive improvements with increasing experience, many would share the feelings of the lecturer when he stated "of this metal . . . we expect much."

If Major Teed had stimulated action on titanium in aeronautical circles on this side of the Atlantic he had indeed rendered valuable service.

R. CHADWICK AND J. W. RODGERS (Imperial Chemical Industries Ltd., Metals Division) *contributed*: The author had attempted to cover a very wide field, and in his anxiety to spotlight some of the novel and unusual features of titanium metallurgy and the problems to which they gave rise, he had, perhaps naturally, tended to quote the more adverse experiences referred to in published literature to the exclusion of others of a less spectacular character. As a result the survey did not fairly reflect the solid progress that had been made, and, moreover, it left the impression that titanium offered no great promise as an aircraft material.

No one would deny that the cost of titanium parts was high, but many of the published figures, especially where alloys were concerned, related to work which was itself in the development phase, and processing costs were accordingly at a high level. The author of a recent article*, quoted by Major Teed, had pointed out that the charges for manipulating so expensive a product were bound to be high, if only to cover adventitious losses of a material of zero scrap value. The present high cost of wrought titanium and titanium parts would be substantially reduced when fabricating processes became well established and were working on an efficient basis. Inflated prices arose from the amount of scrap made at each stage, the value of which had to be added on to the final product. Moreover, as soon as scrap utilisation became possible, price structure would change fundamentally.

The author rightly pointed out that in all existing alloys strength fell off dramatically at temperatures between 400°C. and 500°C., and there seemed to be little chance of effecting much improvement in this situation by further alloying. Unfortunate though this might be for the user, it had the advantage to the fabricator that hot working was relatively easy, in fact the titanium-aluminium-manganese alloy referred to specifically on page 201 as being difficult to forge, could be extruded readily under conditions of temperature and pressure not very different from those used for copper-base alloys. The corresponding alloy steels referred to in Tables XII and XIII would be quite unworkable by such techniques of manufacture. In the temperature range of 880°C. – 980°C. quoted on page 202 titanium alloys could be forged with relative ease and there was no question of requiring heavy and expensive plant. Furthermore, there was no necessity, nor indeed any advantage, in attempting to use controlled atmospheres for pre-heating to temperatures below 1,000°C. With rapid heating at this temperature the scale was thin, and again, contrary to the author's expressed views, it did not interfere in any way with flow of the metal in the die, indeed the scale was, if anything, advantageous. In Table XII, the X 40 cost of forging relative to steel was erroneous, and in their opinion the X 17 cost of machining was also excessive. The X 3½ figure rejected by the author was much nearer the mark, and appeared to be favoured by D. I. Brown, from whose paper the figures were quoted.

Assuming that Tables XII and XIII were substantially correct, and they would undoubtedly represent absolute maximum costs even in the present early stages of development, then, by reference to the data on airline operation quoted on page 196, it would be seen that for the average aircraft (the Viking) the cost of titanium parts would be recovered as revenue arising from the increased available payload in less than three years of the aircraft's life. In the remaining years before the aircraft became obsolete, this additional revenue would provide a handsome return on the extra capital invested by the operator.

*D. I. Brown (1952). *Iron Age*, 170, p. 260, 9th October 1952.

## Major Teed's Reply

SIR ARTHUR SMOUT: He had described himself as being certainly nearer to the optimists than to the pessimists; he had no quarrel with Sir Arthur Smout, who was perhaps the arch optimist, but wished him all success. One appreciated quite well that prices would come down as production processes involved less man power and became more automatic.

He was delighted to hear from Sir Arthur of the new

process, of which there had been rumours. It rather provided the answer to metallurgical friends who insisted that the Kroll process would be with us for a long time, and it looked as though he was going to win on that argument.

He had stated quite definitely in the paper that Fig. 2 illustrated the way in which the Kroll process worked in 1946. He knew that it did not work in quite the same way nowadays; Fig. 2 illustrated the process as it came out of the laboratory and began to be works-operated.

As to production, he believed that ingots were being made nowadays, although not in this country, weighing 1,800 lb., which showed clearly how rapidly and how far titanium had advanced from the laboratory stage.

DR. ALLEN: He was in general agreement with Dr. Allen. The first point he had made was really a matter of their respective degrees of optimism. Though there was no very good yardstick for optimism, he did not think their points of view were very different.

With regard to the continuous process which he had illustrated, he was *officially* informed by the appropriate department in the United States that it really worked continuously. His own feeling was that it would work for a few hours continuously, but that there would have to be a great deal more development before it would work 24 hours a day.

He agreed fully with Dr. Allen's remarks about the impurities in titanium alloys and their relationship to notch sensitivity, and he was glad that Dr. Allen had brought out the subtle point about the relative solubility of oxygen in the $\alpha$ and $\beta$ phases.

The references made by Dr. Allen about titanium with aluminium were extremely interesting. He would have liked to have said something about that himself, for he was aware of what had been said; he had in fact an excellent paper on the subject by Dr. Allen, but since it was marked "Confidential," "Restricted," he had not dared to mention the matter because he did not wish to be led off by MI5 !

PROFESSOR MURPHY: He believed that the ductility of titanium was established by Hunter in 1910. Hunter had obtained pieces of the metal by reducing the tetrachloride with metallic sodium; he had given them a clout with a hammer, and when they flowed and did not break he had rightly decided that the metal was ductile. Subsequently to this he succeeded in making a wire from the titanium so made. This was disappointing in its electrical properties and here his interest in it ceased.

The strong alloy to which Professor Murphy had referred contained chromium and iron, so that it was probably "Ti 150."

PROFESSOR MURPHY: He agreed that it was.

MAJOR TEED: He suggested that Professor Murphy had presented it in rather too favourable a light. It might well be found that if the alloy were used at a temperature of 300°C. or above, it would steadily undergo embrittlement.

PROFESSOR MURPHY: Why use it at temperatures above 300°C.?

MAJOR TEED: He was thinking of using it in a compressor. If it were to be used in a refrigerator, then he agreed that it would do fine.

MR. G. L. BAILEY: He agreed with Mr. Bailey and it might well be that a modest metal suffered from being born in the United States.

The ability to re-melt the scrap was of great importance from the economic point of view, and he was quite optimistic about it when what was called "skull" melting was further developed. Even now swarf could be satisfactorily re-melted, but forgings for which one had no further use presented some difficulty, but with larger equipment he believed that this would ultimately be solved.

MR. S. B. BAILEY: He was in substantial agreement with Mr. Bailey except on one point, and there he was in complete disagreement; this was with regard to the gross revenue earned per annum per pound of disposable load. He hoped Mr. Masefield would take the opportunity to comment.

He liked to hear Mr. Bailey speak with such complete confidence of what could be done by the use of titanium in the power plant; but had Mr. Bailey made a power plant with titanium ? He had taken the precaution to ask three of the largest gas turbine manufacturers what they would save if they used titanium as much as the properties of alloys known to them would allow them to do. Their answers had varied, indicating that one was a little rash to speak with Mr. Bailey's confidence on the matter; one manufacturer had said 8 per cent., another 13 per cent. and another 20 per cent. He would prefer to use the word "may" rather than "will" when speaking of the saving that could be derived from the use of titanium in power plants, but although at present the saving was indeterminate, he was certain it would be worthwhile.

MR. EDWARDS: He was in no degree at variance with his friend and colleague, but he was not so fortunate in his discussions in the United States concerning the fabrication of titanium. When enquiring into the machining problem he had visited one of the great plants there to see the experts. One of them had said that it was necessary to use carbide-tipped tools, which must be kept cool; there must be a blast of liquid $CO_2$ on them, and that necessitated cowling to take the gas away from the operators, and so on. He had written it all down. But within three days he had had the misfortune to meet another expert in the machining of titanium, and had said that he supposed it was necessary to use carbide-tipped tools and a blast of $CO_2$. That expert, however, had said, "Nothing of the sort." He had advised the use of something like a 22 per cent. tungsten tool steel, and an oxy-acetylene flame on the work before it came to the tool !

MR. FORREST: The problem of notch sensitivity was one of extraordinary difficulty. So much depended

upon how the stress concentration was calculated; and different people used different methods. He had included in the paper the Hanink results because they showed the notch sensitivity with a higher degree of stress concentration than did any other results he had been able to find. On the other hand—and he was moving towards the optimists—the metal used for those tests was a year or two old, and with the march of time there had been a definite improvement. Therefore, while it was very prudent to watch the notch sensitivity when the stress concentration factor seemed to be above 3, he did not think that results in the future would necessarily be so disappointing as they were found to be a little while ago.

DR. H. SUTTON: He was delighted to find that there was such a very large measure of agreement between Dr. Sutton and himself. As to Dr. Sutton's two questions—with regard to the first, as a mere metallurgist he did not think he ought to attempt to speak on a question of economics. He did not know what the Aircraft Industry could pay for titanium. It seemed to him that the aircraft manufacturer had to tell his customer that if titanium were used, the price of the machine would be increased by such and such a sum, but the disposable load would also be increased by a perfectly calculable amount; the purchaser, whether civil or military, would then have to determine whether or not this was value for money.

Dr. Sutton's second question was a difficult one. One really wanted to know not only how fast was "very fast," but also the maximum duration of his very fast aircraft's low altitude flight. Because of their very high heat capacity, short-range aircraft of the type Dr. Sutton postulated, were unlikely to attain thermal equilibrium and, as a consequence, the existing light alloys might still prove adequate. Long range, very fast machines were not generally regarded as flying at low altitudes, but should it be necessary for them to do so for such a period of time that the temperature of the surface of the machine became too high to allow current materials to be used, then titanium alloys should, of course, be considered. Their very poor thermal conductivity, however, should not be forgotten—a considerable thermal gradient would exist throughout the material until equilibrium was obtained. This would create stresses which would certainly require thought.

MR. CHADWICK AND DR. RODGERS: Mr. Chadwick and Dr. Rodgers, although two individuals, spoke on titanium as one. They did this with some dogmatism engendered by a very real enthusiasm. The former, he did not resent. The latter he definitely admired.

There was almost agreement between them all as to the present, but more optimism on their part as to the future. Being old, he looked backwards to magnesium when it was in the same state of development as titanium was today. Being young, they looked forward hopefully to the materialisation of their expectations. That was as it should be. Metallurgically, the two metals had something in common. That, he felt, might well prompt a soothsayer to say, "Beware the hexagonal crystal."

Perhaps some of the pronouncements of Mr. Chadwick and Dr. Rodgers had a rather *ex cathedra* quality. For example, commenting on what he had written about forging titanium, they said:—

> "Furthermore, there was no necessity, nor indeed any advantage, in attempting to use controlled atmospheres for pre-heating to temperatures below 1,000°C. With rapid heating at this temperature the scale was thin, and again, contrary to the author's expressed views, it did not interfere in any way with flow of the metal in the die, indeed the scale was, if anything, advantageous."

Mr. Chadwick and Dr. Rodgers might be right, but could we be as certain of this as they were of themselves? In view of the following quotation from a work well known to them*, there might be room for some trifling measure of philosophic doubt?

> "However, for closed-die forging, a somewhat reducing atmosphere is probably best. In fact, considerable experience is yet to be gained as to the best atmosphere to reduce scaling—for titanium scale is abrasive and prevents the metal from moving readily in closed dies."

Mr. Chadwick and Dr. Rodgers had misunderstood his reference to the relative ease of forging titanium and alloy steel, so he would leave that. They, however, stated that his Table XII contained erroneous figures, but had they made a comparable experiment? If not, did they not resemble mentally, although not of course physically, the old lady who, on seeing a giraffe for the first time, vehemently exclaimed, "I don't believe it"—a feeling in one's bones, however intense, was surely no substitute for experimental evidence?

Finally, as to the justification for the use of titanium at its present prices, he refused to be dragged into an economic argument for which he, at least, was most certainly extraordinarily ill-equipped. He commended to these critics his answer to Dr. Sutton on that point.

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**Handbook on Titanium Metal*, 6th Edition. Titanium Metals Corporation.

# Integral Construction

## ITS APPLICATION TO AIRCRAFT DESIGN AND ITS EFFECT ON PRODUCTION METHODS

by

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## 1. Introduction

There has been considerable activity of recent years, particularly in America, in the field of integral structures for aircraft.

The fundamental problem in aircraft structures is to make a relatively thin skin covering take applied compression, shear and bending loads. This has been achieved so far by the attachment of stiffeners, but this requires a large amount of riveting which in itself causes structural inefficiency and also spoils the smoothness of the skin, particularly when laminar flow is desired. Metal gluing shows great advantages over riveting in this respect but it is doubtful whether the bond strength will be great enough to attach very heavy stringers to very thick sheet. Where structural loadings become higher the required thickness of sheet and stringers may make the continued use of riveting difficult, if not impossible. At higher loadings still, the flange of a wing will become one thick sheet, supported only by webs, and this may be described as the "limiting condition" of integral construction, the ultimate form becoming the solid wing.

The advantages claimed for integral construction are potential increase of structural efficiency, reduced assembly time and the maintenance of a smooth outer surface. The American effort has demonstrated that the achievement of these ideals involves machinery and plant of fantastic cost and the research effort so far expended seems to have produced little which is spectacular as regards structural efficiency, although much progress has been made in the achievement of the other ideals. But there is another reason why interest in forms of integral construction is important, if not vital. The increase in speed of modern aircraft into supersonic regions is bringing with it a demand for extremely thin wings, control surfaces, tail planes, fins, and so on. In structural language this means that beams of extremely small depth are required to take ever-increasing loads and meet ever more arduous stiffness requirements.

There are some who consider that integral construction will not just be one controversial solution of many to a particular structural problem but will become the only solution, either in the accepted form or in the ultimate "thick sheet" form. The unfortunate part of the situation is that it is necessary to decide now, if the machinery and plant and "know-how" is to be acquired in time for the production of the next breed of aircraft.

The object of this paper is to examine the trends of structural design necessitated by the aerodynamic requirements of future aeroplanes, to present the information obtained by one particular organisation in its endeavours to produce machined wings, to put forward for the serious consideration of designers some thoughts on what is likely to be required in the future and finally, to give a lead by laying down what raw materials and fabricating machinery are required to meet these requirements.

## 2. Structural Design Trends

As a basis for developing the subsequent argument a rough representation of the dimensional changes of fighter aircraft is shown in Fig. 1, in which aspect ratio, downwind thickness/chord ratio ($t/c$) and sweepback have been plotted against prototype design date. It will be seen that the need in recent years to obtain a high critical Mach number and good transonic performance and characteristics has led to thin wings with considerable sweepback. The future, however, is uncertain in that although the wings will certainly have to be thin, a reversion to the straight wing aeroplane may occur when flight at a Mach number ($M$) of 2·0 is contemplated. A maximum leading edge sweepback of 60° is plotted, this limit being based on aeroelastic requirements. It will also be seen that the aspect ratio which is essentially a compromise between structure weight, induced drag and rolling power has in general been reduced to about half its pre-war value of 6. It is possible that a further small decrease may occur but the drag penalty, especially when manoeuvring, makes any substantial decrease unlikely. The value of $t/c$, which is a compromise between drag and structure weight, is also reaching a limit at around 4 per cent. Fighter weights have increased steadily from about 10,000 lb. in 1940, to the present-day single-engined weight of about 20,000 lb., while a current twin-engined fighter may be at least 30,000 lb.

The effect of these geometric and other changes on the wing design loads is shown in Fig. 2. The construction assumed is an end-load-carrying box spar whose structural chord is 40 per cent. of the aerodynamic chord and the diagram shows mean root boom loads in tons per inch width of flange on a time base. The trends in load are plotted for two hypothetical limiting aircraft. The lower curve is for single-engined fighters with

Section Lecture given on 12th February 1953.

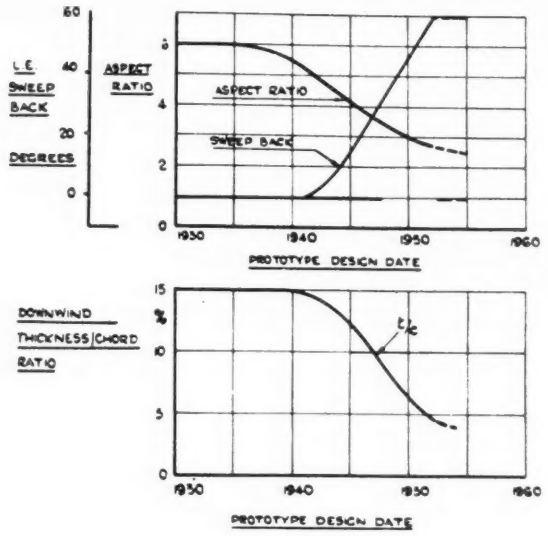



FIGURE 1. Trends in fighter geometric changes.

unswept wings, the increase in boom load being due to the decrease in $t/c$ in association with the weight increase. Thus the design root boom load for a current fighter of this type would be about 7 tons/in. The other curve is for twin-engined fighters and, in addition to the reduction in $t/c$ allowed for in the lower curve, sweepback has been included after 1942 as shown in Fig. 1. Thus a present-day hypothetical twin-engined all-weather fighter design with thin swept wings might have a design root boom load of at least 15 tons/in. It should be noted that the load quoted is only the mean and for a swept wing the root triangle stress concentrations may lead to a 50 per cent. increase over the mean at the rear of the spar.

Increased design loads are not the only penalty for thin wings. The aeroelastic requirements have to be satisfied and these demand a considerable increase in torsion box shear thickness. Fig. 3 shows the spar flange thickness needed to satisfy the aeroelastic requirements plotted against the prototype design date for the same families of aircraft as shown in the previous figures. The assumed construction is again an end-load-carrying torsion box. For the straight-wing fighter the flutter requirement is the more critical and the recent increase in flange thickness is due to the reduction in $t/c$. For the swept-wing fighter, however, the aileron reversal requirement is the more critical. This is due to the flexure caused by the aileron lift giving a downwind twist which adds to the more normal aileron moment effect about the flexural axis. Thus the structural advantages of an unswept wing are considerable, but in both cases the flange thicknesses required are substantially greater than those in use up to the present time.

The diagrams show how suddenly these new structural problems are arising and point to the urgent need for developing structures which are capable of carrying a high load per inch of flange width and which at the same time provide a considerable shear thickness.

In trying to decide what forms of construction are likely to be required to cope with the high structural loadings likely to be encountered, optimum forms of stringer-stiffened sheet have been examined over a wide range of flange loadings, as shown in Fig. 4.

The theoretical optimum based on simultaneous skin buckling and stringer local instability dictates geometrically similar dimensions proportional to flange loading. At high flange loadings this leads to impossibly deep stringers, particularly with thin wings. Apart from the fact that the depth is severely limited, the outstanding edges of the stringers lose their effectiveness, at least for proof loading, by their proximity to the wing neutral axis. At best, even at the ultimate, the effective depth of the flange is significantly reduced. To meet the practical case therefore, an arbitrary limit of 2 in. depth has been imposed, and even this may be considered to be excessive in extreme cases.

This limitation in stringer depth results in a complete change in the geometric dispositions between stringer and sheet at loadings greater than 5 tons/in. At loads up to 5 tons/in. the optimum (stringer area)/(skin area) ratio is nearly unity, but above 5 tons/in. the skin thickness increases rapidly, as does the stringer spacing, which results in a greater proportion of the end-load-carrying capacity being in the skin itself. Because the restricted stringer depth is coupled with an increasing skin thickness the optimum rib pitch decreases.

The minimum load per inch at which integral construction can be used is governed by minimum machining dimensions. It is felt that an acceptable minimum for quantity production is 0·075 in. which gives a minimum design load per inch of 4 to 5 tons/in. for integral construction. The maximum load per inch at which stringer sheet can be used is about 7 tons/in. At this loading the riveting necessary to ensure that the stringers and sheet work in unison becomes excessive, from both production and spacial standpoints. Also, at

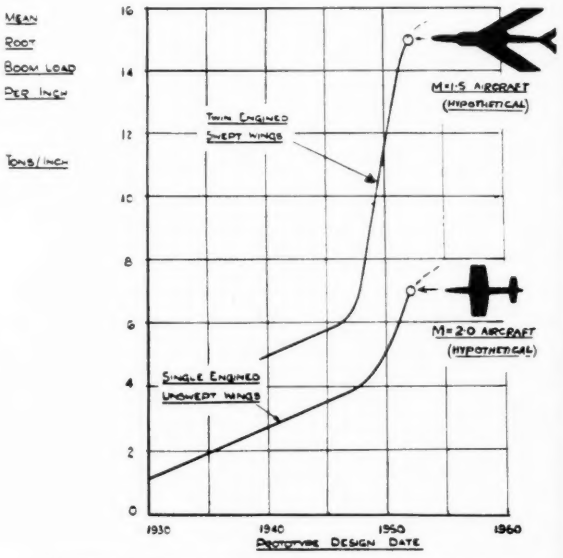



FIGURE 2. Trends in fighter root strength requirements.

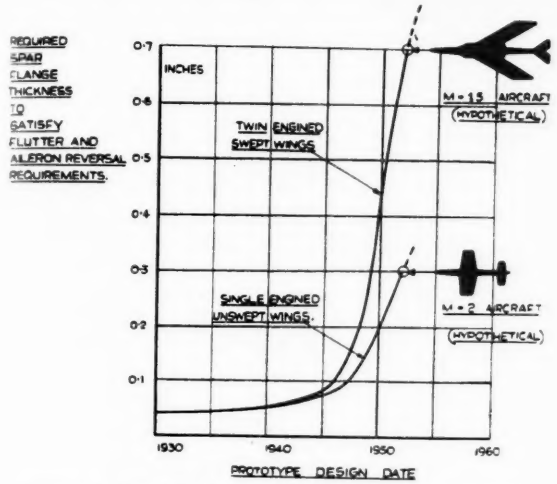



FIGURE 3. Trends in the effect of aeroelastic requirements.

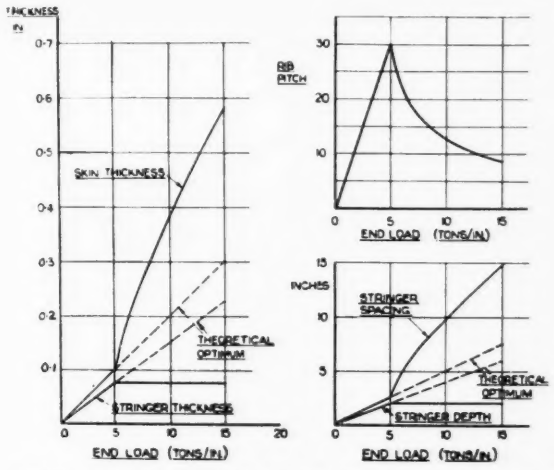



FIGURE 4. Optimum stringer sheet construction (based on a practical maximum stringer depth of 2 in.).

7 tons/in. the skin is about 0·25 in. thick and machining becomes the logical production technique, especially if tapering is required. In the range 4 to 7 tons/in. well riveted stringer sheet and integral construction are comparable from a weight standpoint.

However, as the loads per inch increase the reduced number of stringers, in conjunction with the thicker sheet, leads to further difficulties as regards ensuring that the individual skin panels of the integral construction buckle independently, in other words there is a minimum stiffness of stiffener required to stabilise the skin. Also, the shear stresses imposed by bowing become critical for the stiffeners and departures from the optimum become necessary. The multi-web construction with its deeper stabilising structure attached to the tension flange is far superior in its capacity to provide adequate support for the compression flange. Multi-web construction consists of thick light alloy top and bottom spar flanges with several inter-flange stabilising webs; the ribs are kept to a minimum, root ribs, kink ribs and tip ribs being the only ones retained. Another advantage of multi-web construction is that all the flange stabilising structure is in a spanwise direction where it can be used to carry the vertical shear. This is in contrast to integral construction at high loads per inch since, there, the optimum rib pitch decreases with load causing a substantial increase in useless stabilising structure weight. The transition from integral construction to multi-web is very dependent upon spar depth. A very thin wing would lend itself to multi-web treatment at loadings as low as about 8 to 10 tons/in. However, for a more normal thin wing of about 8 to 10 in. deep the transition range is about 13 to 15 tons/in. The reason why multi-web construction becomes inefficient at lower loads per inch is that the stabilisation structure weight becomes excessive on account of the thinner skin and, as in general the vertical shear will also be low, little advantage is gained from the improved vertical shear-carrying capacity. From a torsion shear thickness standpoint multi-web construction is the best.

The use of multi-web construction with thick sheet can easily be coupled with flange tapering as the machining is simplified by the absence of stringers. Chordwise tapering can be used on swept wings as an economical method of dealing with the stress concentration problems occuring at the rear near the root. Spanwise tapering can be used with the thicker portion inboard, provided that the strength requirements take precedence along the span. If the stiffness requirements are paramount, a reverse taper might be employed since it can be shown that the optimum spanwise distribution of thickness is one that is thicker towards the tip. Thus it is clear that the multi-web design is very flexible from a design point of view.

Figure 5 summarises the applicability of various types of construction for the loading range 0 to 20 tons/in., the construction limits being those set up previously. Plotted against load per inch is the skin thickness for stringer sheet, integral construction and multi-web, the optimum design being plotted in each case. Superimposed on the outside of the graph are four time scales based on Figs. 2 and 3. These show the dates at which the families of aircraft discussed previously fit into the structural picture. For example, they demonstrate that until recently stringer sheet construction has provided both the necessary strength and stiffness for the aircraft being constructed.

Figure 5 further shows that for a current straight-wing single-engined fighter integral construction is applicable. It is worthy of note that an optimum integral construction for such an aircraft might not provide sufficient thickness for aeroelastic needs. In this case the skin thickness would have to be increased as a change to multi-web construction, although giving the correct thickness would result in an even greater weight penalty.

The twin-engined fighter with swept wings, however, needs the multi-web construction, although here again an increase from the optimum thickness would probably be required for aeroelastic reasons. It should be remembered that the strength scale refers to root design and that outer wing design may be less severe, except where

aileron reversal or stiffness requirements are the governing factor. Nevertheless this diagram does show that there is a need for developing both integral and multi-web construction.

Although this review has been dealing with fighters, on account of their thinner wings, modern bombers and civil aeroplanes have design root boom loads which are appropriate to integral construction. For these types of aircraft multi-web construction is not very suitable because of the larger spar depth aggravating the web stabilising problem. Hence, even though a swept-wing fighter appears to need a multi-web design, there remains a vast field for the application of integral construction.

## 3. Early Development of the Machined Wing

In August 1946 Patent No. 22904/46 was filed as a result of some investigations into the production of laminar flow wings by the production engineering department of Sir W. G. Armstrong Whitworth Aircraft Ltd.

What the works thought about the efforts of the Design Office to make laminar flow aeroplanes is contained in the opening sentences of the patent which run —"Considerable difficulty has been experienced in manufacturing the built-up structure of a smooth-surfaced aerofoil, particularly of an aircraft wing, owing to the extremely fine limits of accuracy which are required to avoid disturbing the laminar flow characteristics," and later on, "The main objects of the invention are to provide an improved wing and method whereby the same can be constructed accurately and far more simply and quickly than has hitherto been possible, the method particularly lending itself to repetition production methods." The last part was a particularly vicious dig at the design department. Evidently the production departments considered that the designs they were then struggling with were not, repeat not, suitable for production methods.

The proposals took the form of rectangular extrusions which were milled into channel sections.

The wing section was made up by bolting a number of such channel sections together, thus forming a kind of "plank" construction. For the first trials the largest extrusion which could be obtained was 14 in. × 3 in. × 17 ft. with rounded edges, so that the largest finished machined width that could be made was 10 in. At the time the only machine which could handle this type of work was a spar miller. To form the wing contour on the outer wing surface the cam bars were removed and a form block was placed on the cam brackets. A milling cutter ground to a radius was used. The minimum practical skin thickness when machined in this way was approximately 0·15 in.

As a demonstration of the practicability of the technique this trial proved what it set out to do. Various refinements to the design were then made in order to apply it to a practical example. It was realised from

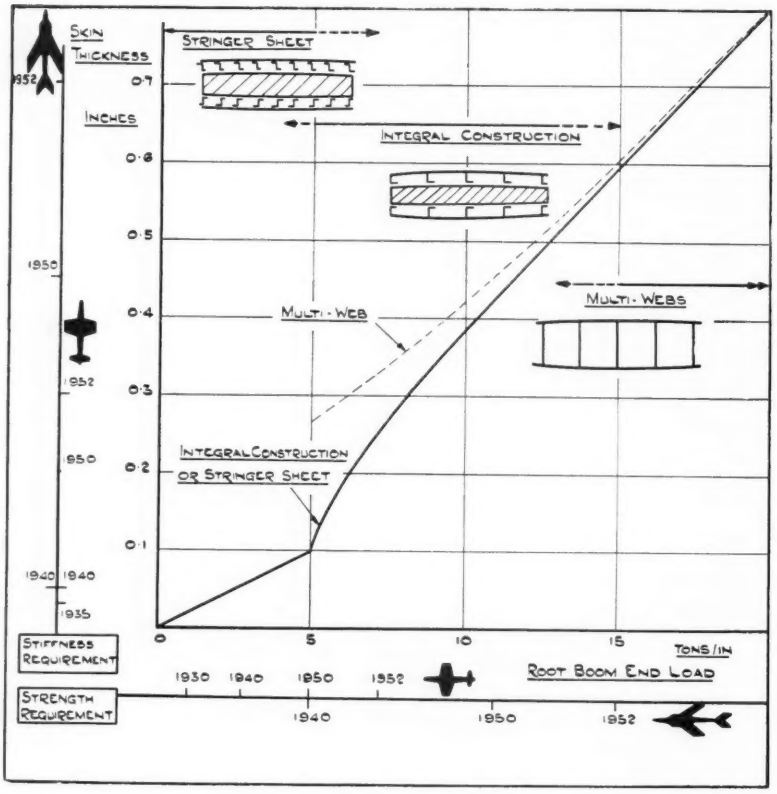



FIGURE 5. Applicability of various types of construction.

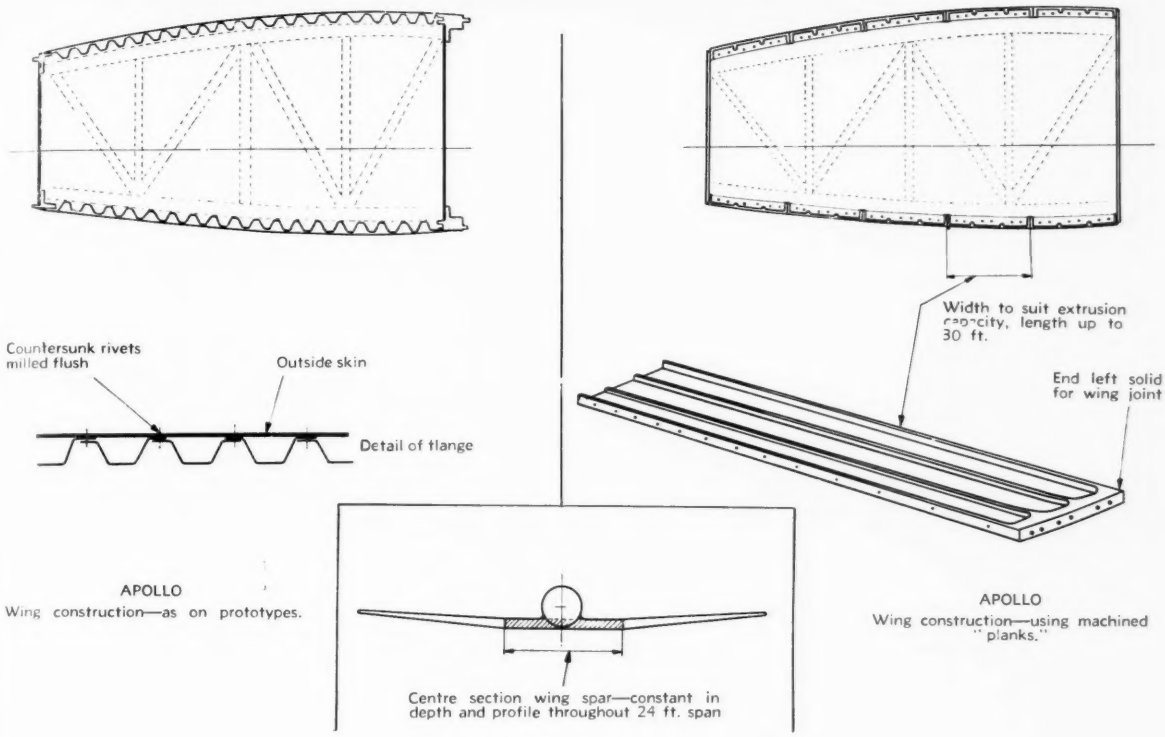

Countersunk rivets milled flush
Outside skin
Detail of flange
APOLLO
Wing construction—as on prototypes.
Width to suit extrusion capacity, length up to 30 ft.
End left solid for wing joint
APOLLO
Wing construction—using machined "planks."
Centre section wing spar—constant in depth and profile throughout 24 ft. span

FIGURE 6.

the first that the construction was heavy and suitable only for high structural loadings. Secondly, intermediate stiffeners would be required to stabilise the skin to withstand a reasonably high compression stress. Thirdly the shape of the stiffeners was far from ideal from a structural point of view. At this time however Z- or T-section stringers were thought to be impracticable, so a design study was made of the application of the best that could be done to the centre section of an Apollo wing. The design worked out is shown in Fig. 6. Two intermediate stiffeners were added to the basic 10 in. wide "planks" enabling the skin thickness to be reduced to 0·10 in.

A detailed study of the relative costs of the machined construction and the existing construction was made showing that, while the cost of material is roughly doubled, saving on details and assembly time using machined panels results in a reduction on overall costs of nearly 30 per cent. Table I gives the details of this investigation. In assessing the actual cost level it should be pointed out that the wing section used was a laminar flow type and the original construction, admittedly expensive, with its closely spaced corrugated stiffeners, was adopted in an effort to secure a transition point as near as possible to the theoretical value of 0·5 of the chord from the leading edge of the wing.

Because of the specialised nature of the original construction the weight of the machined alternative compared favourably and the cost estimates bore out the original contentions of the specification. Tests were made on half-scale compression panels, the results of which (converted to full scale) are shown in Fig. 7. These showed that the obvious improvements of increased depth of stringer, better forms of stringer in the shape of T- or Z-section and a reduction in the ratio of stringer to skin area were necessary before any approach to ideal conditions could be obtained. In fact, also plotted in the curve is the result of a test on a much later panel with an integrally machined Z-section stringer representing the Meteor tailplane construction described later. This result, while still leaving much to be desired from the maximum structural efficiency point

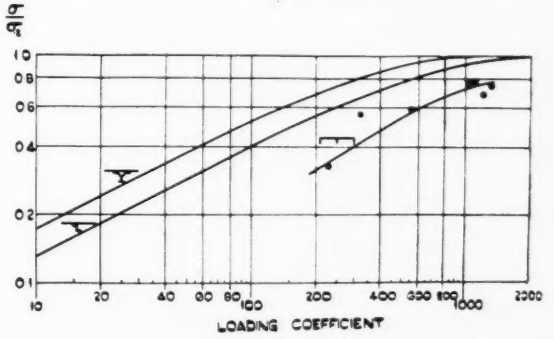



FIGURE 7. Stiffened compression panels. Ratio of realised stress to 0·2 per cent. proof stress ($\sigma/\sigma_2$) plotted against loading coefficient.*

*Loading coefficient (lb./in.²) is defined as $\frac{\text{load per inch width}}{\text{pin-ended length of panel}}$

of view, is certainly a significant improvement on the early construction. Such a construction could not, of course, be universally applied since the dimensions were considered to be practical minima and therefore quite unsuitable for the lightly loaded outer wings of a civil aeroplane. For a rib pitch of 15 in. the flange loading was 3·75 tons/in. width, a figure applicable only to the centre section of the aircraft wing considered. It will be seen from Fig. 5 that this is really not within the range of flange loadings considered to be necessary to justify the use of this form of construction from a structural efficiency point of view.

## 4. The Intermediate Period

Partly because of the luke-warm reception given by the structural experts to this new form of construction, difficult to justify for aircraft designs then current, and partly because of pre-occupation with post-war re-armament, interest in the United Kingdom seemed to flag. Gradually, however, news came of developments in America, and of increasing activities in this field. By now a great deal has been published about the American achievements and it is not intended to repeat the details here. It was not until design studies for aircraft with greatly superior performance were being prepared that it was fully realised that the days of wrapping comparatively thin sheets over an internal rib structure, thereby springing it to the desired contour, were numbered. Indeed it was already being realised that sheets of the thickness required had to be pre-formed by rolling, but before long the required contour would have to be obtained by machining, stretching, or forging. Even in the limiting case, of unstiffened thick sheet, rolls of vastly greater capacity would be needed and machining would probably be necessary to obtain the required surface finish.

The whole problem seemed to take on a new meaning. This new concept was no longer an oddity—it looked more like the shape of things to come, whether

TABLE I

APOLLO CENTRE SECTION WING

PROTOTYPE SPAR COMPONENT

| | *Material* £ s. d. | *Detail labour* £ s. d. | *Installation labour* £ s. d. |
|---|---|---|---|
| Front spar booms | 19 10 0 | 17 10 0 | 30 0 0 |
| Rear spar booms | 99 0 0 | 34 0 0 | 100 0 0 |
| Top panels | 65 0 0 | 900 0 0 | 150 0 0 |
| Ribs 1, 5, 9, 10, 11 | 113 0 0 | 512 10 0 | 138 0 0 |
| Tank bearers | 11 0 0 | 122 0 0 | 40 0 0 |
| Flange supports | 7 0 0 | 24 0 0 | 40 0 0 |
| Tank doors | 55 0 0 | 668 0 0 | 20 0 0 |
| Bolted joints | 42 10 0 | 130 0 0 | 120 0 0 |
| B.J. ribs | 3 0 0 | 21 0 0 | 40 0 0 |
| Totals | £415 0 0 | £2,429 0 0 | £678 0 0 |
| 5% material scrap | 21 0 0 | — — — | — — — |
| 20% G.A. on labour | — — — | 486 0 0 | 136 0 0 |
| | £436 0 0 | £2,915 0 0 | £814 0 0 |

Total cost £4,165 (excluding overheads)

IMPROVED SPAR WITH MACHINED FLANGES

| | *Material* £ s. d. | *Detail labour* £ s. d. | *Installation labour* £ s. d. |
|---|---|---|---|
| Top panels | 344 0 0 | 258 0 0 | 47 0 0 |
| Bottom panels | 281 10 0 | 437 10 0 | 35 0 0 |
| Ribs 1, 5, 9, 10, 11 | 113 0 0 | 512 10 0 | 138 0 0 |
| Tank Bearers | 11 0 0 | 122 0 0 | 40 0 0 |
| Flange Supports | 7 0 0 | 24 0 0 | 40 0 0 |
| Bottom booms | 12 0 0 | 17 0 0 | 30 0 0 |
| Bolts, etc. | 22 10 0 | 20 0 0 | — — — |
| Bottom fairing panels | 3 0 0 | 13 10 0 | 4 0 0 |
| B.J. Ribs | 3 0 0 | 21 0 0 | 40 0 0 |
| Totals | £797 0 0 | £1,425 10 0 | £374 0 0 |
| 5% material scrap | 40 0 0 | — — — | — — — |
| 20% G.A. on labour | — — — | 285 0 0 | 75 0 0 |
| | £837 0 0 | £1,710 10 0 | £449 0 0 |

Total cost £2,996 (excluding overheads)

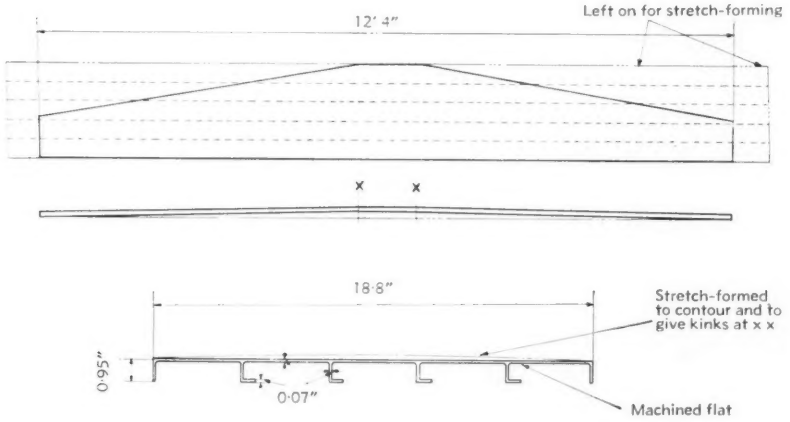


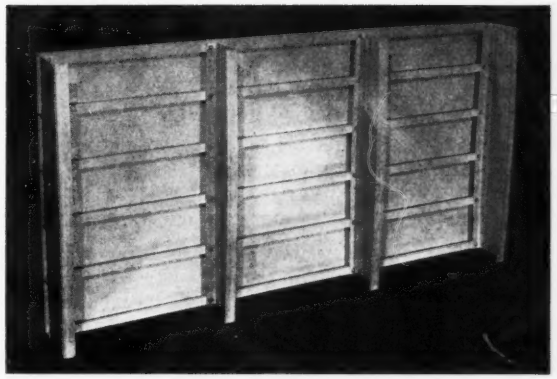

FIGURE 8. Example of a machined flange for tailplane.

we liked it or not. The next question was: were we prepared to meet it? Without a doubt no machinery existed even to make a start. Other requirements, such as producing and machining heavy forgings, required bigger and better machines and a policy of obtaining larger equipment was vigorously pursued. General purpose machines such as the Hydrotel Copy Miller and large Hufford stretcher presses were obtained, new rolling machines installed. In spite of these improved tools doubt still existed as to whether they were of the right kind; were they large enough, could they produce the surface finish required, which method of manufacture would be quickest, cheapest and most satisfactory?

## 5. Recent Developments

Two factors in the present situation are abundantly clear. Large new expensive machinery is required and, what is even more important, all the theoretical conjecturing must be backed up by some practical exercises. Research of this kind is extremely expensive and it is not easy to find anyone to foot the bill. After many proposals had been made a contract was placed to produce three Meteor tailplanes with the box spar flanges of integral construction. From a structural point of view the exercise is not very satisfying, as this particular tailplane is too thick and too lightly loaded. However, valuable lessons are being learnt on the practical side, particularly as most of the work can be done on existing machinery, at least after a fashion. Originally it was intended to produce the three specimens in identical ways, *i.e.* by machining to the desired shape from the solid without any further manipulation. Fig. 8 shows the construction adopted for the main box spar.

Soon after the job was begun it was realised that an opportunity existed for examining other potentially



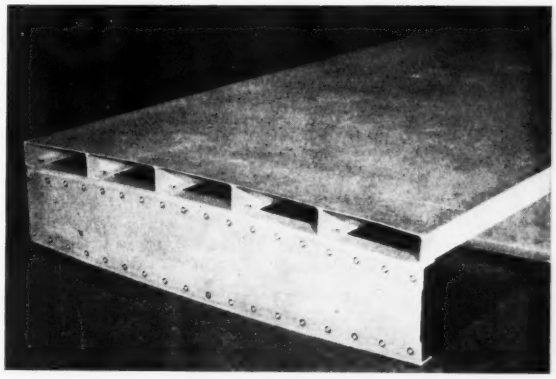


FIGURE 9. A trial piece produced with a spar miller—Stage II —machined flat from solid billet.

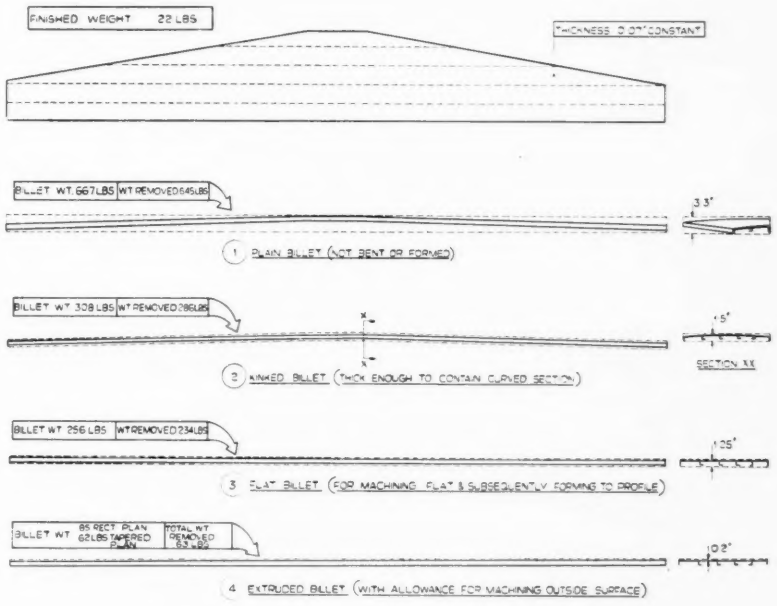

FINISHED WEIGHT 22 LBS
THICKNESS 0.07" CONSTANT
BILLET WT. 667 LBS
WT REMOVED 645 LBS
.33"
1 PLAIN BILLET (NOT BENT OR FORMED)
BILLET WT. 338 LBS
WT REMOVED 316 LBS
.15"
SECTION XX
2 KINKED BILLET (THICK ENOUGH TO CONTAIN CURVED SECTION)
BILLET WT 256 LBS
WT REMOVED 234 LBS
.125"
3 FLAT BILLET (FOR MACHINING FLAT & SUBSEQUENTLY FORMING TO PROFILE)
BILLET WT 85 RECT. PLAN 62 LBS TAPERED PLAN
TOTAL WT REMOVED 63 + 85
.02"
4 EXTRUDED BILLET (WITH ALLOWANCE FOR MACHINING OUTSIDE SURFACE)

FIGURE 10. Alternative forms of billet for tailplane flange.

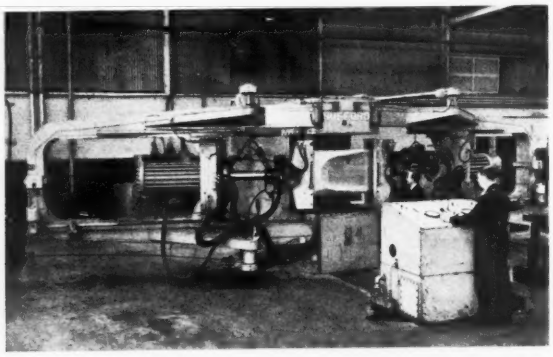


FIGURE 11. The Hufford stretch-forming machine.

more economical ways of doing the job. Firstly, it would be easier if the stiffeners and skin could be machined flat and afterwards formed to the curved contour. Secondly, one of the most serious criticisms of the machining method is the great amount of metal to be removed and the excessive time required to remove it. Material extruded or forged to nearly the required shape is obviously preferable. It was found that extrusions of tube form complete with stiffeners could be obtained in the United Kingdom, but machinery for opening it out in even the moderate length required for this job was not available. There seemed little point in making provision for this if the stretch forming of the flat flange produced by machining was not successful. The revised programme therefore is in three stages:—

*Stage I* Machined from solid to required contours without any further forming process.

*Stage II* Machined flat from solid billet and stretch-form subsequently.

*Stage III* If Stage II proves successful, split a tubular extrusion, flatten out and stretch-form to contour.

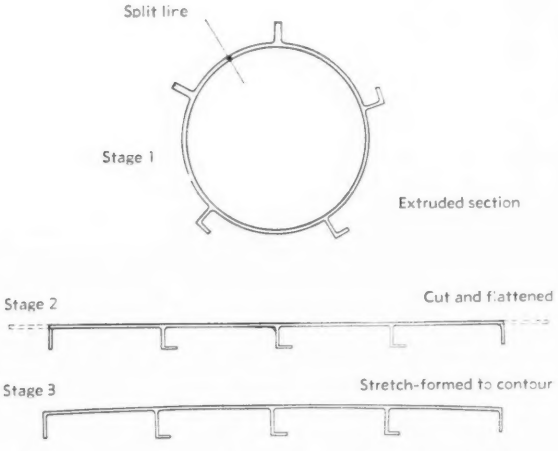



FIGURE 12. Method of producing an integrally stiffened flange from an extrusion.

The machining of the outside skin profile and the rough form of the stringers in Stage I is done on a Cincinatti Hydrotel Copy Miller and the final shape of the Z-section stringers is obtained by adapting the head of a planer miller. For Stage II a spar miller is used which gives a much higher cutting speed than the Hydrotel. A trial piece produced by this method is shown in Fig. 9, the slight curvature being produced by clamping down on to the ribs. This piece was tested in compression and the results, previously referred to, are plotted in Fig. 7. Careful choice of the billet, together with slight setting, can minimise the amount of machining required as illustrated in Fig. 10, as to avoid joints the flange is made continuous as near as possible from tip to tip, thereby involving a central kink. It is proposed to stretch-form the flat machined flange (or the flattened extrusion) spanwise in the Hufford stretch-forming machine shown in Fig. 11.

Naturally, tapered structures cannot be dealt with in this way. To overcome the difficulty, the flange is machined full width for stretching and afterwards tapered in plan form by removing the unwanted material. For Stage III, extrusions of the type shown in Fig. 12 can be obtained now, to order, sufficiently wide for the Meteor tailplanes. True there is a limitation on the diameter and billet size for larger jobs, but there seems no reason why several of these could not be bolted together, rather like the "plank" construction already described.

Another comparatively recent trial piece shown in Fig. 13 represents the centre section and inboard portions of a highly swept tailplane spar flange. It was produced from a casting, and this method shows great promise from a manufacturing point of view. Structurally, however, the material properties are not at all good. The actual piece illustrated was made in a low grade light alloy merely for demonstration purposes. The development of high grade castings of this sort would have a wide application.

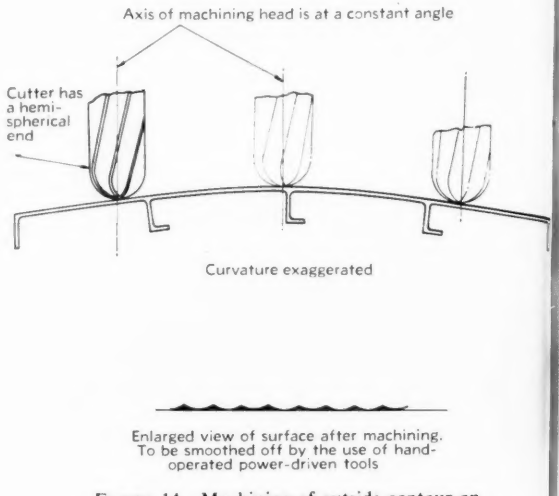

Axis of machining head is at a constant angle
Cutter has a hemi-spherical end
Curvature exaggerated
Enlarged view of surface after machining. To be smoothed off by the use of hand-operated power-driven tools

FIGURE 14. Machining of outside contour on Cincinnati Hydrotel.

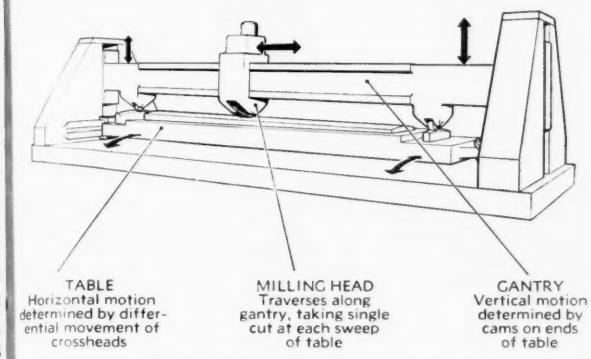


TABLE
Horizontal motion determined by differential movement of crossheads
MILLING HEAD
Traverses along gantry, taking single cut at each sweep of table
GANTRY
Vertical motion determined by cams on ends of table

FIGURE 16. Aerofoil profile milling machine (basic presentation).

## 6. Lessons being Learnt from the Practical Work already in Hand

Billets just large enough were available for the job in hand and the requirements for future developments will be discussed later.

To mill the skin down to the thickness required it must be extremely well supported. For milling in the flat, suction beds will be required and a bed large enough to do the present job is being construced. When machining on the Hydrotel in the contoured shape, accurate form blocks will be required as a minimum; whether these too will be required to be suction beds will be determined in the near future. However, the ball-ended cutter of the Hydrotel is most unsuitable for the finish required. Fig. 14 shows that the final surface is inevitably composed of a series of ridges, the height of which is determined by the feed for each successive cut. The smaller the feed the better the surface finish but the longer the machining operation. Some process of final smoothing down is therefore required and at the moment there seems little alternative to some kind of hand process. A photograph of the Meteor tailplane flange on the Hydrotel machine is shown in Fig. 15. Other contour machines for producing an acceptable finish without final processing have been investigated but none exist. Even the Giddings and Lewis Spar Miller as used by

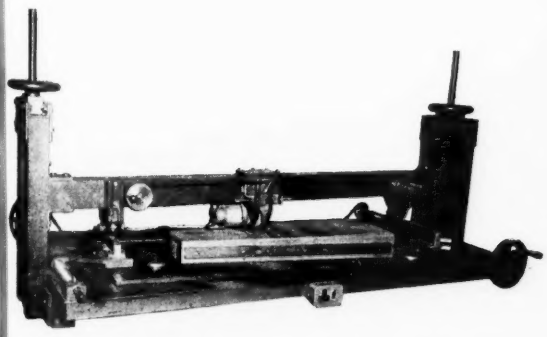


FIGURE 17. A model of the milling machine shown in Figure 16.

FIGURE 13. The centre section and inboard portions of a tailplane spar flange produced from a casting.

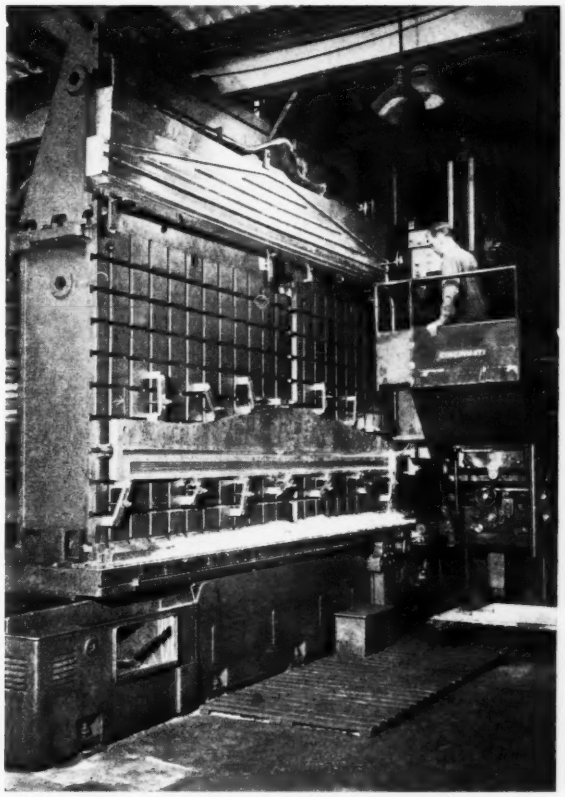


FIGURE 15. The Meteor tailplane flange on the Hydrotel machine.

Lockheeds in America will not carry out chordwise contour milling at present.

In an attempt to resolve this difficulty the Design Department collaborated with the Production Departments and produced a simplified solution to the problem, making assumptions which only the Design Department are in a position to lay down. These are that all lines along a wing surface may be straight line generators in a spanwise direction.

As a result of these deliberations a machine was devised on the lines of Fig. 16 to which Patent No. 12391/52 applies, this being somewhat unusually sponsored by the Design Department. The paramount feature of this machine is its simplicity. No fancy electronic operating gear is required, the only attribute to its efficient working being a hydraulic servo; this is necessary to ensure that correct following occurs on steeply sloping surfaces, such as would occur nearing the leading edge. A very successful model has been made of the machine as shown in Fig. 17. Another point is that in Stages II and III the stretching process is limited by the capacity of the 50 ton Hufford stretcher, indicating that, if this method has the possibilities hoped for in dealing with heavier structures, much larger stretch formers will be required. The amount of stretch it is intended to apply is 0·4 per cent corresponding to a stress of 18 tons/in.², involving a pull of 36 tons on the nominal area.

## 7. Thick Sheet Construction

Examination of a possible swept-back thin-wing design, somewhat as envisaged by Clifton and Keith

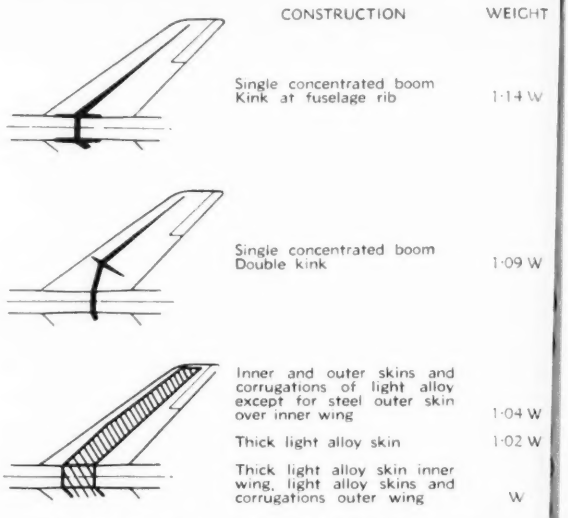

CONSTRUCTION
WEIGHT
Single concentrated boom
Kink at fuselage rib
1·14 W
Single concentrated boom
Double kink
1·09 W
Inner and outer skins and corrugations of light alloy except for steel outer skin over inner wing
1·04 W
Thick light alloy skin
1·02 W
Thick light alloy skin inner wing, light alloy skins and corrugations outer wing
W

FIGURE 18. Comparative weights of different types of construction.

Lucas in recent papers, has been made to determine the most efficient form of wing construction. The details of the investigation are given in Fig. 18. This leads to the conclusion that firstly, a box spar is the most efficient structure, and also that the unstiffened thick plate, supported by webs, gives the lightest form of construction, at least for the heavily loaded centre section. Outboard of the transport joint, where the structural loading is lower, some weight can be saved

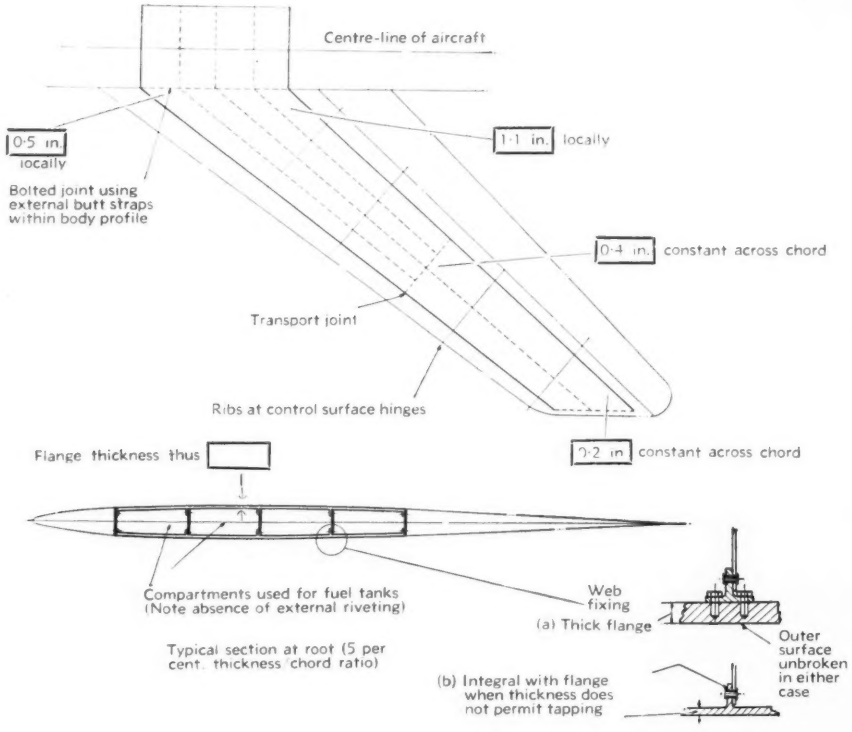

Centre-line of aircraft
0·5 in. locally
1·1 in. locally
Bolted joint using external butt straps within body profile
0·4 in. constant across chord
Transport joint
Ribs at control surface hinges
Flange thickness thus
0·2 in. constant across chord
Compartments used for fuel tanks (Note absence of external riveting)
Typical section at root (5 per cent. thickness/chord ratio)
Web fixing
(a) Thick flange
Outer surface unbroken in either case
(b) Integral with flange when thickness does not permit tapping

FIGURE 19. Wing construction using machined flanges and multi-webs.

by adopting a stiffened skin supported by ribs but the weight penalty involved by continuing the simple inner wing construction is small. The average flange loading at the root is 18 tons/in. width, well inside the range in which it is suggested, in Fig. 5, that a thick sheet is the appropriate form of construction.

The suggested design is shown in Fig. 19. The average thickness at the root is 0·7 in. tapering to 0·4 in. at the transport joint. An additional complication is that, due to concentration of load at the rear web of a swept-back wing, a local thickness of 1·1 in. is required. Ideally a billet 20 ft. long, 1·5 in. thick and 5ft. 6 in. wide would be required initially flat (method (3) in Fig. 10) rolled to approximate contour and machined to the thickness required as shown in Fig. 19.

The method of attaching the webs is by tapping into the thick skin. On the outer portion, where the skin is thinner, ridges to attach the webs will be machined integrally. The billet required in this instance is 20 ft. long x 5 ft. wide x $1\frac{1}{4}$ in. thick. The finished skin thickness tapers from 0·4 in. at the inboard end to 0·2 in. at the tip. The final contour can be produced by the A.W.A. skin miller on the outside and a very close approximation to the required taper, both chordwise and spanwise, can be obtained by milling the inside on the same machine with suitable cam bars. Much reduction in machining time would ensue if plates could be produced nearly to the required thicknesses, leaving only a light finishing cut to be taken by the milling machine.

## 8. Present Limitation in Billet Size

The weight of billet required for the centre section is 2,500 lb. Billets up to one ton have been cast successfully in the United Kingdom in most light alloy materials, the preferred one being D.T.D. 687. However the size of finished billet is severely limited at present, for hot-rolled plate, by heat treatment plant and roller levelling machines, to 14 ft. long and 4 ft. 6 in. wide. Thus, unless the capacity of these plants is increased, very wasteful joints both spanwise and chordwise will have to be introduced. Where forged plates are concerned, such as have been used for the exercise on the Meteor tailplane, the present limit is about 14 ft. long x 2 ft. wide. Tremendous advantages would accrue if forged plates with rough stringers formed on them could be produced for integral construction, thus reducing the amount of subsequent machining required.

However, present plant limits the amount by which the forged billet can be reduced in thickness, $1\frac{1}{2}$ in. being the adjudged minimum which can be used with safety.

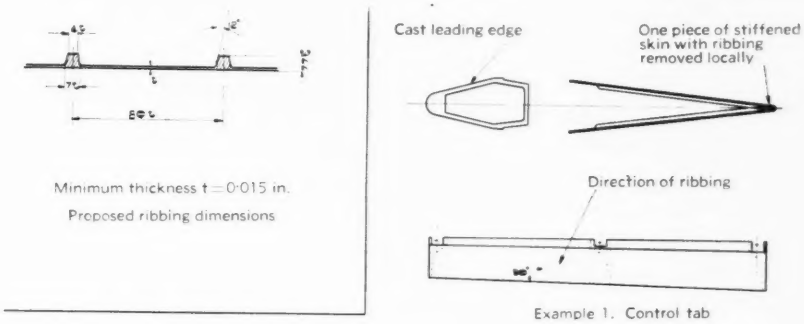



FIGURE 20. Uses of integrally-stiffened ribbed sheet.

## 9. Ribbed Sheet

One form of basic material which can be legitimately described as integral construction is the formation of stiffening ribs on light gauges of sheet during the manufacturing process. The uses for such a material are many. Leading edges, trailing edge fairings, control tab surfaces and even the surfaces of the controls themselves, are all possible fields of application. To stimulate interest by the material manufacturers, an investigation was made into the possibility of standardising requirements. The resulting dimensions put forward for consideration are shown in Fig. 20. Formation of these ribs is, of course, no easy matter. The possible methods are rolling, forging or machining.

The machining process has been used by several organisations and, by using a suction bed to hold down the sheet, appears to present no particular difficulties. The use of this method is therefore purely one of economics. An example of its use for simplifying, cheapening and reducing the time for production of a Meteor tab is also shown on this diagram, together with suggested areas of application for a control surface and trailing edge fairing. By its use the number of separate parts of the tab, excluding rivets, can be reduced from 102 to 58. The number of rivets is reduced from 830 to 240. The cost, excluding the skin in the first instance and the ribbed sheet in the second, is reduced from £13 to £7. As the cost of the plain skin is only 3/9d. it can be seen that the ribbed sheet could be 32 times as expensive to break even on a cost basis. Details of the cost break down are given in Table II. The saving in assembly time would still show a valuable credit balance, quite apart from the improved appearance and serviceability of the finished components.

TABLE II

COMPARISON BETWEEN CONTROL TABS

(*a*) SCHEDULE OF PARTS FOR CONVENTIONAL CONSTRUCTION

| *Item* | *Description* | *No. off* | *Remarks* |
|---|---|---|---|
| 1 | Spar | 1 | In 4 separate pieces |
| 2 | Ribs | 17 | All different |
| 3 | T.E. member | 1 | |
| 4 | Nose member | 1 | In 4 pieces |
| 5 | Top skin | 1 | |
| 6 | Bottom skin | 1 | |
| 7 | Auxiliary spar | 1 | To give continuity at hinges |
| 8 | Reinforcement plates | 6 | |
| 9 | Brackets | 13 | 10 different kinds |
| 10 | Bearings | 4 | |
| 11 | Packings and channel sections | 6 | |
| 12 | Special bolts | 3 | |
| 13 | Ordinary bolts, nuts and washers, etc. | 25 | |
| 14 | Mass balance washers | 16 | |
| 15 | Rivets and self-tapping screws | 830 | 10 different kinds |
| | Number of parts = 932 | | |

(*b*) SCHEDULE OF PARTS FOR RIBBED SHEET CONSTRUCTION

| *Item* | *Description* | *No. off* | *Remarks* |
|---|---|---|---|
| 1 | Ribbed skin | 1 | |
| 2 | Spar (casting, includes mass balancing and nosing) | 1 | |
| 3 | Hinge brackets | 6 | |
| 4 | Lever brackets | 2 | |
| 5 | Reinforcement plates | 6 | |
| 6 | Bearings | 4 | |
| 7 | Special bolts | 3 | |
| 8 | Ordinary bolts, nuts and washers | 25 | |
| 9 | Rivets and self-tapping screws | 240 | Future development might employ adhesive which would further reduce riveting |
| | Number of parts = 298 | | |

MANUFACTURING COSTS

| | *Material* £ s. d. | *Labour* £ s. d. |
|---|---|---|
| Making detail parts | | 1 5 6 |
| Assembly of ribs, spars, etc. | | 2 0 0 |
| Assembly of hinges | | 6 6 |
| Assembly of skins | | 2 18 9 |
| Assembly of balance weights, etc. | | 1 4 9 |
| Assembly of trailing edge | | 1 2 6 |
| Miscellaneous work and finishing | | 16 6 |
| | £3 9 9 | £9 14 6 |
| Total: £13 4 3 | | |

| | *Material* £ s. d. | *Labour* £ s. d. |
|---|---|---|
| Ribbed skin | | |
| Ribbed skin mill off and fold | | 4 9 |
| Cast spar and machining | 1 18 3 | 12 0 |
| Make and fit item 5 (6 off) | 6 | 5 6 |
| Make and fit hinge attachment to spar | 15 0 | 18 0 |
| Trimming of folded sheet | | 6 6 |
| Drill and rivet | 5 0 | 3 8 |
| Sealing of ends, etc. | 1 0 | 2 6 |
| Bearings | 12 7 | |
| Housing bolts | 5 0 | |
| Miscellaneous material and labour | 4 3 | 5 3 |
| | £4 1 7 | £2 18 2 |
| Total: £6 19 9 | | |

In addition to its application to primary members, such components as floors, partitions and bulkheads, equipment mountings etc., could be considerably simplified by its use. The usual conflict arises between depth of rib required from structural considerations and that convenient for production.

The dimensions shown are considered to be the minimum to make the proposition worth while. Unfortunately also, the material is best used with the ribs running across the width of the sheet, which again makes manufacture more difficult. There is no doubt, however, that the provision of such a material is well worth while and could be used to advantage in a wide range of applications.

## 10. Conclusions

The aim of this paper is to attempt to demonstrate that, if structural engineers are to keep pace with the rapid developments in engines and aerodynamics they will need new techniques, the foundations for which must be laid immediately. The scope of the paper, being within the confines of a Section Lecture, is parochial in that all the work described is that of one firm, *i.e.* Sir W. G. Armstrong Whitworth Aircraft Limited. It is realised that a great deal of other work is in hand in the United Kingdom and it is hoped that it may be possible in the not too distant future to correlate all the data and information which must be fast accumulating. The fact that in the future the structure weight of aircraft is inevitably increasing, due to unfavourable overall dimensions, makes the need for high structural efficiency imperative. Unless the necessary plant and raw materials are made available the make-shift structure will not be worthy of the brilliant conceptions of the aerodynamicist and the engine designer.

Many of the assumptions made in developing the argument are rather arbitrary and in some cases the evidence is, of necessity, sketchy. Any attempts at forecasting the future can never be precise, but it is claimed that the trends are unmistakable and they so clearly indicate shortcomings in the methods now available for manufacture that urgent steps are required to meet the future situation. That the government recognises the need for shouldering some of the burden which such steps indicate is evidenced by the fact that a production research section has been set up to investigate just these problems, and furthermore, to place development contracts for research into new processes and machines.

At present it is true to say that the structural designers by no means speak with one voice and in general are wary of committing themselves. If this paper contributes in any way to laying down a clearer picture of what is likely to be wanted, then it will have justified itself.

ACKNOWLEDGMENTS

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# An Introduction to the Helicopter

by

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## Introduction

The helicopter, because of its complicated nature, provides the mathematician with a delightful set of problems on which to exercise his ingenuity, but the purpose of this paper is to interpret the functioning of the helicopter in terms of its physical aspects.

The paper is divided into three main parts:—

1. General Performance
2. Control and Stability
3. Rotor Vibration Problems.

## *Notation*

| | |
|---|---|
| $\alpha$ | blade angle of attack |
| $\beta$ | blade flapping displacement |
| $\gamma$ | blade lagging displacement (in plane of hub) |
| $\psi$ | blade azimuth position measured from downwind position |
| $V$ | forward speed |
| $v_i$ | rotor induced velocity |
| $V_N$ | component of flight velocity normal to tip path plane |
| $V_R$, $V_F$ | velocity components normal to blade due to coning of blade and forward speed |
| $V_T$ | resultant air velocity to blade in plane of rotation |
| $D$ | drag |
| $T$ | thrust |
| $\Delta T$ | increment of thrust |
| $W$ | weight |
| $\theta$ | collective pitch |
| $\omega$ | angular velocity of rotor rotation |
| $M$ | mass |

## 1. General Performance

The power required to fly a fixed wing aircraft in steady flight may be divided into three main parts, namely, the induced power of the wings, the profile power of the wings and the parasite power of the rest of the aircraft. The helicopter power required can also be split into three similar components:—

(*i*) The induced power of the rotor
(*ii*) The profile power of the rotor
(*iii*) The parasite power of the attached body.

### 1.1. INDUCED POWER

To produce thrust, a rotor must impart momentum to a mass of air. In hovering, the air above the rotor is at rest and must be accelerated through the disc to produce the necessary change of momentum. For a given weight of helicopter, the larger the rotor disc the smaller the necessary change of velocity through the disc for a given change of momentum. The induced power required is the product of force (thrust) and the velocity of air through the disc; therefore the larger the disc the less the power required to lift a given weight.

When the rotor is moved through the air, either vertically or horizontally, it encounters a larger mass of air per unit time which increases with speed, and therefore it has to impart less velocity to that mass in order to produce the required thrust. A typical induced power required curve against forward speed is shown in Fig. 1.

### 1.2. THE PROFILE POWER

This is the power necessary to rotate and translate the blades through the air. An accurate assessment of this is difficult and tedious, since it involves integrating the drag of each section of the blade as it performs one revolution. The incidence of each section will change cyclically once per revolution and the angle of attack of each section is different. The Reynolds number of each section is different and varies sinusoidally once per revolution. It is not usual to go to these extremes in order to calculate performance, but to use a mean profile drag coefficient for the rotor, based on assessment of test results. The profile power in hovering can easily be calculated from this quantity and the effect of forward speed is obtained as an additional factor of the hovering power, proportional to the square of the forward speed.

### 1.3. PARASITE POWER

This is the power required to translate all the remaining drag-producing parts of the helicopter, the fuselage, undercarriage, rotor hub and the various pieces of operational equipment which usually change the aerodynamicist's original conception. The parasite power of present-day helicopters is very high and accounts for about 40 per cent. of the total power required in cruising at, say, 90 knots. On the Bristol 171 the drags of the fuselage, undercarriage and rotor hub are approximately equal.

Performance of future designs will probably be improved by cleaner fuselage design, faired or retracting undercarriages, faired hubs and the effect of size, increasing the Reynolds numbers. It should be possible, in the next generation of helicopters, to reduce the drag during cruising to 25 per cent. of the total power required.

These three items make up the power to be supplied to the rotor for steady flight. To be added to this are

*Lecture given before the Graduates' and Students' Section on 18th November 1952.*

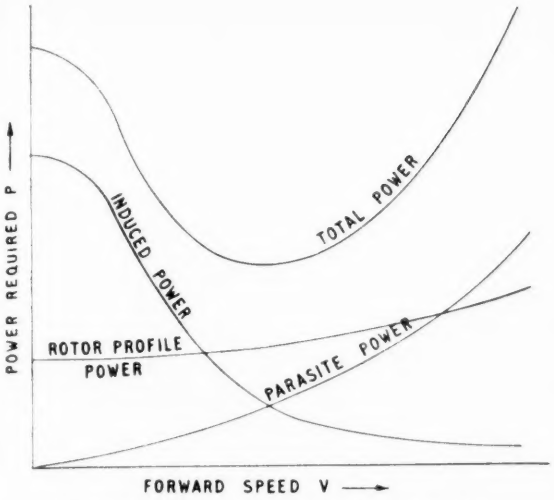


FIGURE 1. Power required *versus* forward speed.

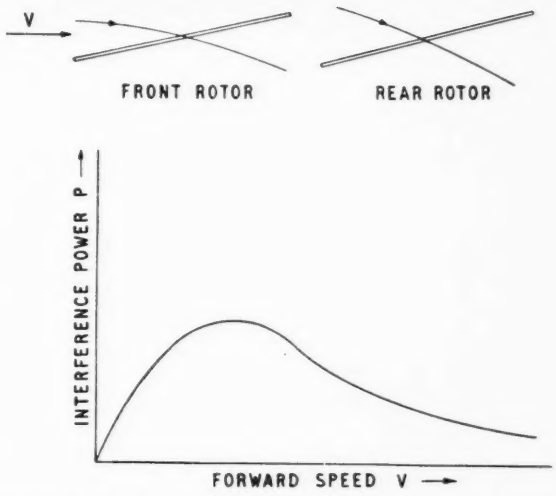


FIGURE 2. Interference power at rear rotor *versus* forward speed.

the power losses in the transmission, usually assessed for "good" gears at one per cent. of rotor power for each stage of spur gearing and two per cent. per stage for bevel gearing. Also, there is the power necessary for torque compensation. With the single main rotor type of helicopter, with vertical tail rotor, this varies from 7 to 8 per cent. in hovering to 3 to 4 per cent. in cruising flight.

Tandem helicopters are arranged with rotors turning in opposite directions so that torque compensation is unnecessary. Most present-day helicopters have a rather marginal vertical performance and this saving in power for torque compensation would be about sufficient to double the vertical rate of climb. The remaining item is the power required to cool the engine. This is now of the order of 8 per cent. of rotor power in hovering but more careful ducting and fairing should reduce this figure to 5 per cent. The main point to watch in these cleaning-up operations is that the performance gained by ducting and fairing is not outweighed by the actual weight of the modifications.

The helicopter trend for civil operation is aimed at services from city centre to city centre and for this purpose multi-engined helicopters must be forthcoming, capable of operating with the critical engine failed. For a twin-engined helicopter this means a climb on one engine of not less than 200 ft./min. It can be seen from Fig. 1 that the twin-engined helicopter meets this case since the ratio of the power required to hover to the minimum power for level flight is of the ratio of 2:1. This means that the twin-engined helicopter designed for a reasonable vertical performance on both engines will have an acceptable rate of climb on one engine.

The single rotor helicopter has a slight advantage over the tandem for the single-engined case at minimum power. The downwash from the front rotor in forward flight induces a downward component of velocity in the air stream entering the rear rotor disc. The rear rotor therefore has to perform extra work in order to maintain its thrust, equal to the product of the rear rotor thrust and the velocity induced at the rear rotor by the front rotor. In hovering, the slipstreams from the rotors are vertically downwards and there is no interference. As the helicopter moves forward the interference increases until it reaches a maximum at approximately the speed for minimum power and then decreases again (Fig. 2). At minimum power speed the interference is of the order of 8 per cent. of the power required by the rotors, whereas the tail rotor of the single rotor machine needs only 5 per cent. The interference power on tandems can be reduced by raising the rear rotor above the front rotor, but structural weight limitations become prohibitive if this is carried too far.

So far the single rotor and tandem rotor helicopters have been considered from the viewpoint of power required and it has been shown that the tandem is better for hovering performance because no torque

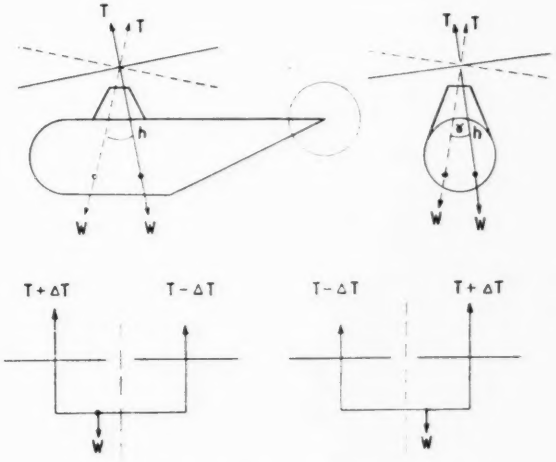


FIGURE 3. C.G. ranges for single rotor and tandem rotor helicopters.

compensation is required, but the single rotor machine has a slight advantage for multi-engined machines where performance with critical engine inoperative is necessary.

## 2. Control and Stability

Performance is not the only criterion for helicopter design; it is also necessary to have a wide range of general operational utility. This requirement inevitably leads to a wide range of centre of gravity movement due, for example, to indiscriminate loading of passengers.

The single rotor helicopter has an angular range through which its rotor can be tilted both fore and aft and laterally. To hover, the thrust vector must pass through the centre of gravity, neglecting such effects as moment on fuselage due to downwash and offset flapping hinges. The fore and aft and lateral c.g. ranges are therefore given by the product of the angular rotor tilt and the vertical height of the rotor above the c.g. (Fig. 3). Change of c.g. also involves change of fuselage attitude, which may prove inconvenient for the tail rotor for manoeuvres close to the ground.

A c.g. movement on a tandem rotor helicopter can be balanced by a differential change of thrust on the rotors and this can be achieved with little change of fuselage attitude. Comparable figures of longitudinal c.g. ranges for single and tandem rotor helicopters would be of the order of 5 in. and 30 in. respectively. The figure of 30 in. could very easily be increased.

Before studying the principles of changing trim on a helicopter it will perhaps be better to consider how to trim a helicopter in steady forward flight. Considering a rotor as a propeller with its axis vertical there is a certain angle of blade incidence which will support the propeller stationary relative to the free air. As the propeller moves forward the induced velocity drops, and so does the necessary pitch on the propeller to provide thrust (Fig. 4). At the same time it is necessary to tilt the propeller forward to overcome the parasite drag of the attached body. The induced velocity decreases

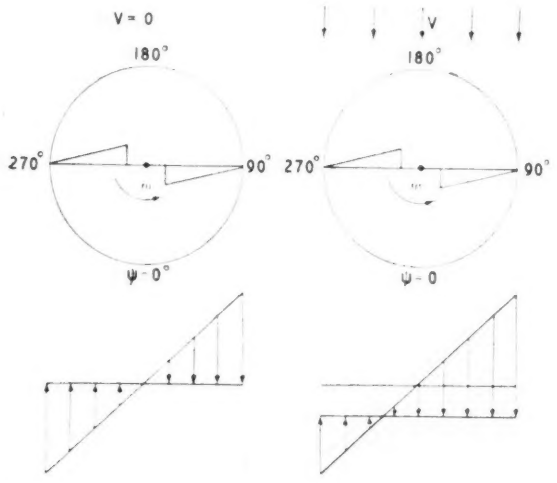


FIGURE 5. Distribution of air velocity, relative to the blades, across the rotor for hovering and forward flight.

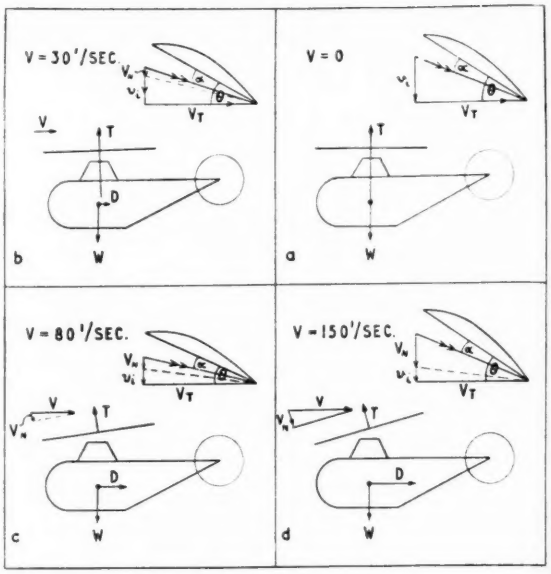


FIGURE 4. Collective pitch to trim in level flight *versus* forward speed.

rapidly at first as speed increases, while the parasite drag increases slowly (Fig. 1); thus the required collective pitch decreases with forward speed until a point is reached where decrease of induced velocity with speed is small, and at about this point the "speed squared" effect on parasite drag starts to become appreciable. Here the propeller has to be tilted forward considerably so that the horizontal component of the thrust vector balances the drag. There is a component of horizontal flight path velocity normal to the disc, increasing the inflow through the propeller, and the collective pitch has to be increased to obtain the necessary thrust. The shape of the curve of collective pitch to trim against forward speed is almost identical with the total power required curve (Fig. 1).

This, however, is not the full story. As the propeller moves forward the blade moving in the direction of motion (known as the advancing blade) experiences a resultant air velocity equal to the sum of the rotational speed and the forward speed, while the blade moving in the opposite direction to the motion, the retreating blade, experiences an air velocity equal to the difference of these (Fig. 5). The propeller will experience more lift on the advancing side than on the retreating side, which will cause it to roll. The rolling moment can be overcome by cyclically varying the pitch on the blades as they rotate. This is illustrated in Fig. 6(*a*) and is known as a pure feathering rotor. The plane of the rotor remains in the plane of the hub and the thrust vector is normal to the rotor disc.

Alternatively, if the blades are hinged to the hub so that they are free to flap upwards normal to the plane of the hub and the axis of the hub is tilted forward, the tip plane of the blades remaining as for the feathering rotor, the result is the same. The advancing blade has decreased incidence and the retreating blade increased

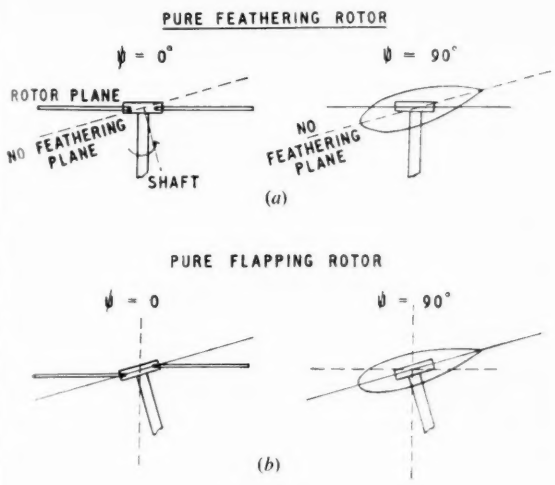


FIGURE 6.

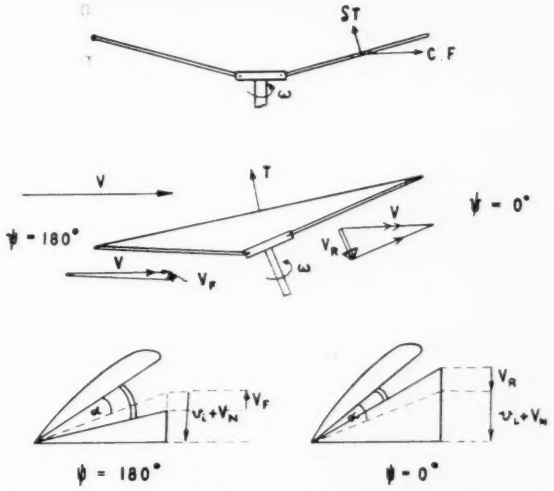


FIGURE 7. The effect of forward speed and coning angle on blade angle of attack when in the fore-and-aft position.

incidence (Fig. 6(*b*) ). This is known as a pure flapping rotor and is the principle on which most helicopters are designed.

Considering this last point from a slightly different angle, with a hinged rotor moving forward the advancing blade has maximum air velocity, causing maximum lift. The motion of the blade must be such as to cause it to remain in equilibrium. The blade will flap upwards with a velocity causing a reduction in incidence. On the retreating side the blade will have a downward flapping velocity causing an increase in incidence. Blades in the upwind and downwind position have zero flapping velocity since no change in blade incidence is required to maintain equilibrium. Thus, measuring the blade azimuth position from downwind the blade flapping velocity is $\beta z \sin\psi$, giving the flapping displacement $\beta z - \cos\psi$, *i.e.* zero displacement in the advancing and retreating blade positions, maximum upward flapping displacement on the forward or upwind blade and maximum downward flapping displacement on the downwind blade. These conditions are those necessary to fulfil the conditions for a pure flapping rotor. The basic effect of the trim with the flapping rotor is that the plane of the rotor tilts back from the plane of the hub with increase of forward speed.

The effects of blade inertia and aerodynamic damping have been neglected. The flapping blade may be represented as a damped single-degree-of-freedom system being forced at its resonant frequency. The solution for such a system in resonance shows that the force leads the displacement by 90°.

With a flapping rotor there is also a lateral tilt of the rotor disc downwards on the advancing blade side. Considering Fig. 7, the lift moment causes the blade to cone upwards. Because of the forward speed there is a small upward component of velocity on the forward blade, causing an increase of incidence and on the aft blade there is a downward component causing a decrease in incidence. Displacement lagging 90° behind force causes maximum upward flap on the retreating blade and maximum downward flap on the advancing blade.

It has now been shown that in order to fly a helicopter with a pure flapping rotor system in a trimmed condition, the rotor tip path must tilt back and laterally downwards towards the advancing blade. The thrust from the rotor being normal to the tip path plane, the hub axis must be orientated to obtain the correct balance of forces.

To change speed on a helicopter it is necessary to tilt the thrust vector, *i.e.* the rotor tip path in the direction of the required speed change. The rotor blades are freely hinged to the hub so that if the hub axis is tilted (say forward) no moment can be transmitted to the blades, and the tip path plane remains in its original position. Because of the hub tilt, the advancing blade experiences decreased incidence and the retreating blade increased incidence. The retreating blade has upward flapping velocity to maintain equilibrium, causing maximum upward displacement at the aft blade position, due to the 90° phase shift between flapping velocity and displacement. Similarly the forward blade flaps downwards and the tip path plane therefore tilts forward to follow the hub plane, or more correctly, the control plane.

In practice it is not convenient to make the mechanical hub tilt, so this part of its function is replaced by a tilting control orbit. Referring to Fig. 6(*b*) it is seen that in steady trimmed flight there is no cyclic change of pitch relative to the control orbit. The effective hub tilt is obtained in practice by applying a cyclic change of pitch to the blades relative to the mechanical hub by means of a swash plate, or the "Bristol" Spider control. There is no applied cyclic feathering relative to this spider or swash plate orbit and the blade flapping motion so far discussed takes place relative to this orbit.

Tilting the control orbit forward causes a tilt of the rotor tip path plane and of the rotor thrust vector. The increased forward component of thrust causes linear acceleration and the increased moment of the thrust

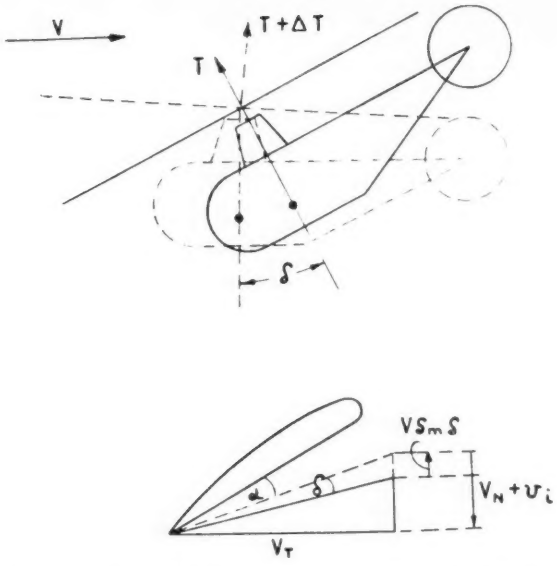


FIGURE 8. Rotor stability with change of fuselage incidence.

vector about the c.g. causes nose-down pitching acceleration. This gives a satisfactory control for the single rotor helicopter, but in the tandem helicopter with its large moment of inertia, the pitching acceleration would be very small from rotor tilt alone. The longitudinal control for a tandem could be obtained by application of differential collective pitch to the rotors. This would give good control of pitching, but linear acceleration would be sluggish since large changes of fuselage attitude would be necessary before linear response was obtained. A satisfactory control has been obtained on the Bristol Type 173 by mixing the two systems to give a control response similar to that obtained with a single rotor helicopter. As the control stick is pushed forward, tilting both rotors forward, the collective pitch on the front rotor is reduced and that on the rear rotor increased.

Having discussed the method of obtaining the control to trim a helicopter and the control to change the trim of a helicopter it remains to consider the stability problem, which will be limited to static stability only.

It has been shown that the rotor plane tilts back from the control orbit by an amount proportional to the forward speed. Thus an increase in speed causes the rotor to tilt backwards. The thrust vector is tilted back causing a deceleration, returning the helicopter to its original speed. The helicopter is thus statically stable with speed.

If the helicopter is displaced in pitch, say nose up, the tilt back of the control orbit causes an increase in incidence on the advancing blade and a decrease in incidence on the retreating blade. This causes the rotor disc to flap back following the plane of the control. This backward tilt causes a reduction in the inflow of the flight velocity through the disc (Fig. 8) which gives an increase in incidence to all elements of the rotor, and thus an increase in thrust. The advancing blade obtains a greater lift increment than the retreating blade, causing a further flap back of the disc. A nose-up displacement of a single rotor helicopter causes an increased thrust moment about the c.g. in the direction of the displacement. Thus the helicopter is unstable with angle of attack. In the tandem helicopter the tilts of the rotors give moments about the c.g. which are additive, but the increases in the thrust vectors act in opposite directions. The tandem is therefore less unstable with angle of attack than the single rotor helicopter.

With the tandem, once a pitching velocity (nose up) has built up, there is an increased velocity through the front rotor which has the effect of reducing incidence and therefore thrust, and a reduced velocity through the rear rotor giving an increased thrust, the result being a restoring moment.

## 3. Rotor Vibration

The subject of rotor vibration is so vast that a course of lectures would be necessary to cover present knowledge, which is far from complete. Three types of oscillations which take place in the plane of the rotor disc will be discussed:—

(*i*) Torsional oscillations.

(*ii*) Rotor whirling.

(*iii*) Ground resonance.

These particular oscillations arise because the blades are articulated in the drag plane in order to reduce root bending stresses and to reduce blade vibration due to the flapping motion in forward flight. The two-bladed rotor provides special cases in the general problem of drag hinge oscillations, so for brevity this section is

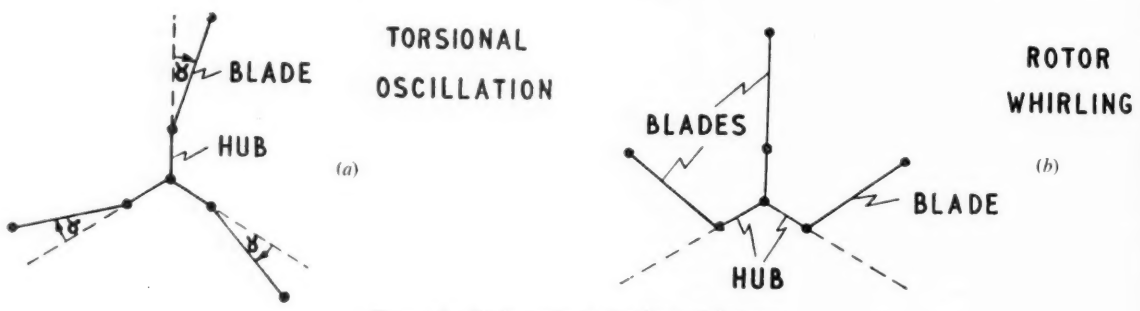


FIGURE 9. Blade modes in the plane of the rotor.

confined to the three-bladed rotor, which represents the general *n*-bladed rotor.

One possible mode of oscillation for a three-bladed rotor is obtained by blades moving in phase with each other, giving a torsional oscillation (Fig. 9*a*). Another mode is given by the blades all folding together (Fig. 9*b*). This causes rotor whirling and is not a true rotor oscillation but the motion does produce a helicopter vibration. The only other possible mode is for the blades to move out of phase with each other. It is unlikely that the blades would oscillate with unsymmetrical phasing and with the three-bladed rotor the blades would be expected to be phase-displaced by 120°. This is the case with the phenomenon known as ground resonance.

### 3.1. TORSIONAL OSCILLATION

Figure 10 shows that blade equilibrium in the drag plane is obtained when the resultant vector of drag and centrifugal force passes through the drag hinge. To simplify the picture two point masses may be selected to represent the blade, one at the drag hinge and the other at the centre of percussion, such that their masses and their first and second moments about the drag hinge are equal to those of the blade.

If the blade is displaced from the equilibrium position, there is a centrifugal restoring moment proportional to the displacement, giving an equivalent stiffness about the drag hinge. There is a fixed relationship between the drag hinge displacement and the angular displacement of the blade tip mass about the hub centre. Therefore the stiffness about the drag hinge can be expressed as a stiffness about the hub centre. The torsional oscillation of a three-blade rotor can be reduced to that of a two mass system joined by a spring, where the spring stiffness varies with the square of the rotational speed (r.p.m.).

### 3.2. ROTOR WHIRLING

A helicopter with blades locked at the drag hinges possesses certain natural frequencies on its undercarriage. When the rotor r.p.m. is equal to the one of these natural frequencies, a divergent instability occurs similar to the instability which occurs in the whirling of a shaft, *i.e.* when the undercarriage spring is neutralised by the centrifugal force (C.F.) of the rotor. Because of the articulation, the instability occurs at a rotor r.p.m. less than the natural frequency, dependent on the ratio of the blade mass to helicopter mass and on the drag hinge offset.

### 3.3. GROUND RESONANCE

Figure 11 shows an idealised helicopter mass-stiffness system vertically reduced to one plane. The fuselage vibrations are therefore limited to linear motions. Numerous investigations have shown that the general motion of the blades can be reduced to that of a mass with two degrees of freedom normal to one another. There is thus a three-degree-of-freedom system with stiffness between the blade mass and hub

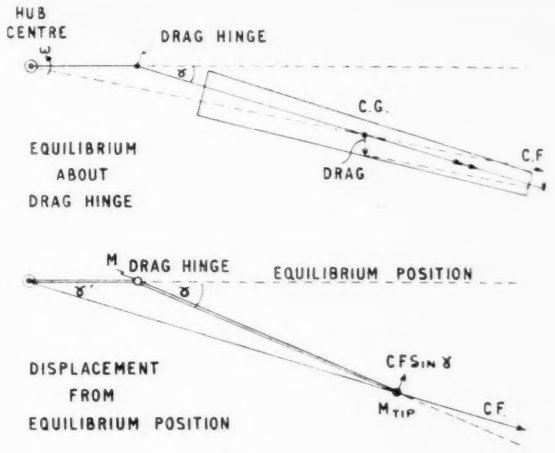


FIGURE 10.

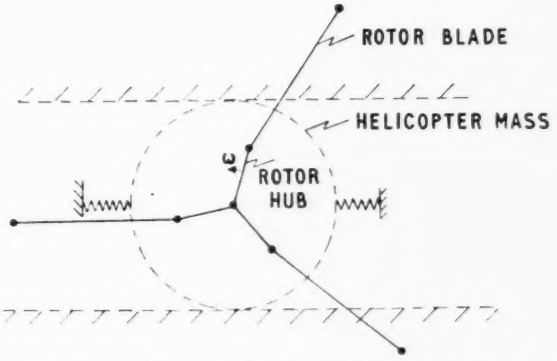


FIGURE 11. Idealised helicopter dynamical system in the plane of the hub.

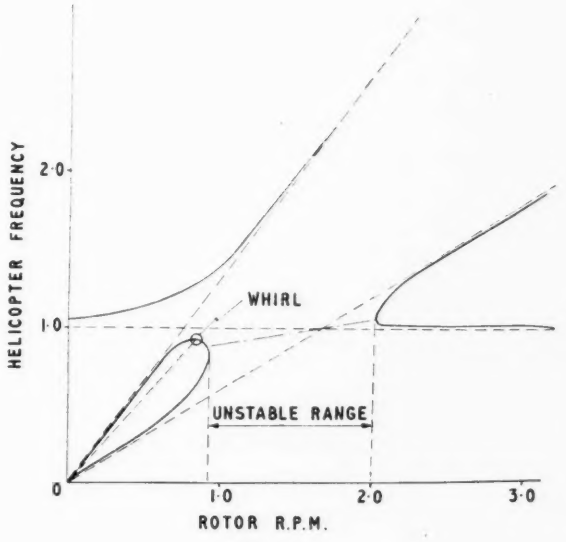


FIGURE 12.

varying as the square of r.p.m. The system can be shown to be unstable for a range of r.p.m.

Figure 12 shows the natural frequencies of the system against rotor r.p.m. For low and high r.p.m. there are three natural frequencies of the system, but in the middle of the r.p.m. range there is only one natural frequency. The other solutions are complex, giving an unstable divergent oscillation. The intersection of a 45° slope through the origin gives the position of rotor whirling. Theory shows that the unstable range can be closed by applying damping in the undercarriage and between blades and hub but it is the product of the damping forces, and not the individual quantities, which are important.

A dynamic model was constructed at the Bristol Aeroplane Co. Ltd. with a linear scale of 1/8 and a mass scale of 1/70, preserving the same non-dimensional parameters as the full scale rotor. It was demonstrated that in the unstable range the blades oscillated 120° phase displaced. This means that the centre of gravity of the three rotor blades rotates at a constant arm about the centre of the hub (the arm is proportional to blade amplitude), in the opposite direction to the direction of rotation of the rotor and at the angular frequency of the blade oscillation. Thus there is an out-of-balance force rotating at a speed equal to the difference between rotor speed and blade frequency, causing the helicopter fuselage to oscillate at this frequency.

The effect of damping was also investigated. Fig. 13 shows how the damping product reduces the width of the unstable range, and that the damping raises the whirling speed until it reaches a steady value equal to the helicopter frequency with blades locked.

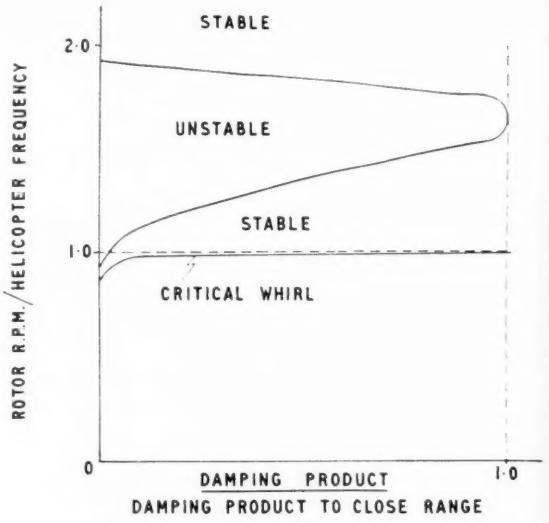


FIGURE 13.

ACKNOWLEDGMENTS

The author acknowledges the permission of the Bristol Aeroplane Co. Ltd. and the Ministry of Supply to publish certain information given in the paper and to show the film which followed the lecture. He also thanks Mr. R. Hafner for his contructive criticisms and Messrs. Jones and Simon for their help in compiling the paper.

Any opinions expressed in the paper are the author's own and not necessarily the considered opinion of the Bristol Aeroplane Co. Ltd.

# TECHNICAL NOTES

*The increasing flood of technical information makes it difficult to publish even abstracts of such information and it has become still more difficult to publish technical items of information which do not reach the status of full-length papers.*

*Under this general heading of TECHNICAL NOTES it is hoped that members of the Society, and indeed all those who read* THE JOURNAL, *will help in contributing just those very items of useful information which normally might not see the light of the printed page.*

*There will be no set form for these Notes. They may be illustrated or not. They can be short papers of a thousand or two thousand words; or abstracts and comments upon unpublished papers or upon published papers with a limited circulation; or notes of some interim results of research in hand and notes for further research; or in the form of a letter raising technical points or asking technical questions; or letters commenting on Notes already published.*

*These pages are intended to be a technical forum where members can argue and discuss; where they can inform and be informed; and pass on their own experience, or air their technical difficulties. Contributions will be published as soon as possible after they are received and will be eligible for* JOURNAL *Premium Awards.*

*No member need ever say that his particular subject does not get discussed in the pages of* THE JOURNAL. *He can always raise it himself, for these pages are his pages.*

*Four Notes are published this month, two from overseas: a definition of the centre of shear, a theoretical treatment of aileron reversal at transonic speeds, a design method for eliminating wall effects in axial-flow compressor stages and an account of some pressure tests on flat rectangular plates. This last, by Oaks, is the result of tests made at the Royal Aircraft Establishment on behalf of the Society's Structures Committee. A similar investigation by Dickinson and Hadley of Armstrong Whitworth Aircraft Ltd. was published in the January Technical Notes. The type of box, method of providing rigid edge support and the correction of the results for initial deflection of the plate are somewhat different in the report published this month. Comparison of the techniques and the results obtained is interesting.*

## *The Centre of Shear of Aerofoil Sections*

by

JOHN A. JACOBS

*(Professor of Applied Mathematics, University of Toronto)*

CONSIDER a cantilever beam of uniform cross section whose generators are parallel to the $z$-axis and whose lateral surface is free from surface tractions. The line of centroids of the cross sections in the unstrained state is taken as the $z$-axis, and the $x$- and $y$-axes are the principal axes of the cross section at the centroid of the fixed end $z=0$.

The other end of the beam ($z=l$) is subject to forces which reduce to a single force with components ($W_x$, $W_y$, 0), transverse to the $z$-axis, acting through the load point $L$ of this end section (*see* Fig. 1). The co-ordinates of $L$ are taken as ($p$, $q$, $l$).

There has been much disagreement in the literature as to the location of the centre of shear. Osgood[1] has reviewed the subject and has shown that the disagreements arise from the assumptions of different boundary conditions. The centre of shear is usually defined as that point of the cross section at the free end at which a transverse load must be applied in order that no rotation of the free end may occur in its own plane. But the position of the centre of shear as thus defined is not unique. Even for a given material, it is not a property of the cross section alone.

The foregoing definition is inadequate because it regards the cross sections as displaced without relative movements of points within them. This relative movement, however, exists in general and different elements of area in the cross section will suffer different amounts of rotation. Thus, for an arbitrary cross section, to make the definition of the shear centre precise, it is necessary to specify which point of the cross section has zero rotation. Such specifications have been made, explicitly or implicitly, by several writers in their definition of the centre of shear.

With the conventional notation, denoting the $z$-component of the rotation at any point by $\omega_z$, the local twist is defined at any point to be $\partial\omega_z/\partial z$. The local twist thus measures the relative rotation of neighbouring cross sections of the beam. The mean value $\theta$ of the local twists over any section is the value of the local twist at the centroid of the section. The most natural definition for the centre of shear is the load point when the mean value of the local twists taken over the cross section is zero, *i.e.* when the local twist at the centroid of the section is zero. This is the definition adopted by Stevenson[2], and restated by Specht[3] in his discussion

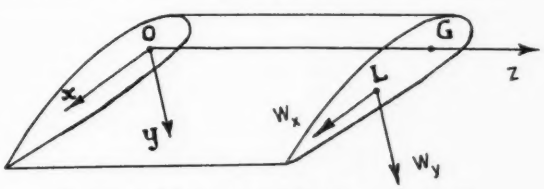


FIGURE 1. Scheme of co-ordinate axes and loading of the cantilever beam.

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of Osgood's paper[1]. This definition is in effect that used by Goodier[4] in a paper in 1945, and given in the second (but not in the first) edition of Timoshenko's[5] book. It is this definition that is used in this paper. Many writers, including Stevenson and Timoshenko, call the centre of shear, the centre of flexure or the flexural centre.

## 1. THE CENTRE OF SHEAR AND THE CENTRE OF LEAST STRAIN

Trefftz[6], however, obtains the position of what he calls the centre of shear from energy considerations, by postulating that the elastic strain energy should be a minimum. The point he obtains is not the same as the centre of shear as defined previously and, to avoid confusion, it will be called here the point of least strain. The co-ordinates of this point are $(p_1, q_1)$ where

$$p_1 = -\frac{1}{I_x}\int_S y\phi\, dS, \quad q_1 = \frac{1}{I_y}\int_S x\phi\, dS \quad (1)$$

where $\phi = \phi(x, y)$ is the torsion function for the cross section and $I_x$, $I_y$ are the moments of inertia of the cross section about the axes of $x$ and $y$ respectively. It is also possible (from Stevenson's paper) to obtain the co-ordinates $(p_2, q_2)$ of the centre of shear in terms of the torsion function $\phi$ only, although the result is not nearly so simple as the expressions (1) giving the position of the centre of least strain. Explicitly,

$$\left.\begin{aligned} p_2 &= -\frac{1}{I_x}\left\{\int_S y\phi\, dS - \frac{\sigma}{2(1+\sigma)}\int_S \left(x^2\frac{\partial\phi}{\partial y} + x^3\right) dS\right\} \\ q_2 &= \frac{1}{I_y}\left\{\int_S x\phi\, dS - \frac{\sigma}{2(1+\sigma)}\int_S \left(y^2\frac{\partial\phi}{\partial x} - y^3\right) dS\right\} \end{aligned}\right\} \quad (2)$$

It can be seen that the equations (1) and (2) yield the same point if Poisson's ratio $\sigma$ is zero.

## 2. APPLICATION TO COMPACT SECTIONS

If these results are applied to a semi-circular cross section where the load is applied parallel to the bounding diameter (*see* Fig. 2), it is found that the distance of the centre of shear from the centre $O'$ of the circle forming part of the boundary is

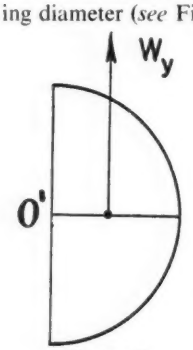

FIGURE 2.

$$\frac{8a}{5\pi} + \frac{32\sigma a(10-\pi^2)}{15(1+\sigma)\pi^3},$$

where $a$ is the radius, whereas the distance of the centre of least strain is $8a/(5\pi)$. Thus for $\sigma = 0{\cdot}3$, the difference between these two points is only 0·2 per cent. of the radius. This extremely small difference between the centre of shear and the centre of least strain is true for all compact sections. It is, of course, very much simpler to determine the position of the centre of least strain rather than the centre of shear (compare formulae (1) and (2)). Even in the simple example of the semi-circular cross section quoted, the simplification is enormous. It is of interest, therefore, to estimate the difference between the two points for a long thin section such as an aerofoil, where the location of the centre of shear is necessary for flutter calculations.

From the equations (1) and (2) the difference between the co-ordinates of the centre of shear and the centre of least strain can be obtained.

Writing $\chi = \psi - \frac{1}{2}(x^2+y^2)$, where $\phi$ and $\psi$ are conjugate functions, so that

$$\left.\begin{aligned} \frac{\partial\chi}{\partial x} &= \frac{\partial\psi}{\partial x} - x = -\frac{\partial\phi}{\partial y} - x \\ \text{and} \quad \frac{\partial\chi}{\partial y} &= \frac{\partial\psi}{\partial y} - y = \frac{\partial\phi}{\partial x} - y \end{aligned}\right\} \quad (3)$$

from equations (1) and (2)

$$p_2 - p_1 = \frac{\sigma}{2I_x(1+\sigma)}\int_S \left(x^2\frac{\partial\phi}{\partial y} + x^3\right) dS$$

$$= \frac{-\sigma}{2I_x(1+\sigma)}\int_S x^2\frac{\partial\chi}{\partial x}\, dS \quad (4)$$

and

$$q_2 - q_1 = \frac{-\sigma}{2I_y(1+\sigma)}\int_S \left(y^2\frac{\partial\phi}{\partial x} - y^3\right) dS$$

$$= \frac{-\sigma}{2I_y(1+\sigma)}\int_S y^2\frac{\partial\chi}{\partial y}\, dS \quad (5)$$

## 3. APPLICATIONS TO A THIN AEROFOIL SECTION

The particular aerofoil chosen for the investigation is the C.7, details of which are given in Table I. Ordinates are equidistant from the centre line, which is a circular

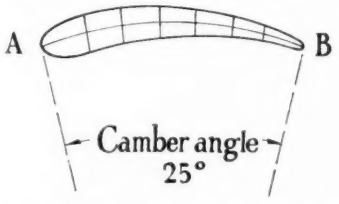

FIGURE 3.

arc (radius $r$), the camber angle being 25° (*see* Fig. 3). This particular section has been used for turbine blades.

TABLE I

C.7 AEROFOIL

| *Station: per cent. arc* | *Blade ordinate (10 per cent. thick aerofoil)* |
|---|---|
| 0 | 0 |
| 1·25 | 1·51 |
| 2·5 | 2·04 |
| 5 | 2·72 |
| 7·5 | 3·18 |
| 10·0 | 3·54 |
| 15 | 4·05 |
| 20 | 4·42 |
| 30 | 4·86 |
| 40 | 5·00 |
| 50 | 4·86 |
| 60 | 4·43 |
| 70 | 3·73 |
| 80 | 2·78 |
| 90 | 1·65 |
| 95 | 1·09 |
| 100 | 0 |

Leading edge radius—12 per cent. maximum thickness.
Trailing edge radius— 6 per cent. maximum thickness.

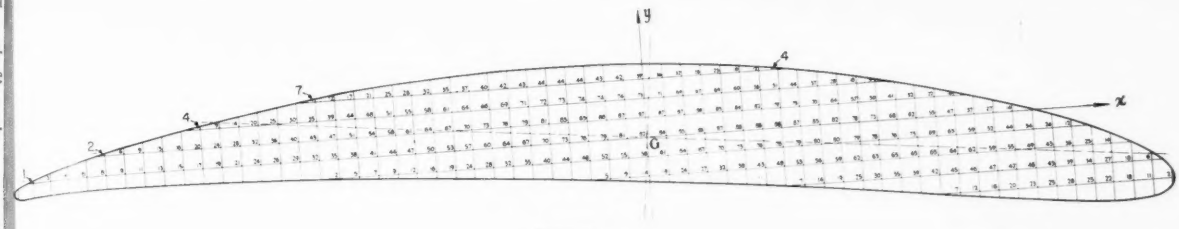

FIGURE 4.

The centroid and the principal moments of inertia at the centroid are obtained by numerical methods.

The scale chosen is such that the chord $AB = 30{\cdot}5$ inches (corresponding to $r = 70$ inches). The principal axes make angles 84° and 174° with $AB$, and $I = 42{\cdot}3$ in.$^4$, $I_y = 785$ in.$^4$

The torsion problem for the cross section is solved by relaxation methods. The area is covered with a ¼-inch network and a solution is obtained of the equation $\nabla^2\chi = -2$, with the boundary condition $\chi = 0$. Fig. 4 gives values of $36{,}000\chi$. Values of $\partial\chi/\partial x$ and $\partial\chi/\partial y$ are obtained numerically, and finally the integrals

$$\int_S x^2 \frac{\partial\chi}{\partial x}\,dS \quad \text{and} \quad \int_S y^2 \frac{\partial\chi}{\partial y}\,dS \text{ are evaluated.}$$

From (4),

$$p_2 - p_1 = \frac{\sigma r}{1+\sigma}(10{\cdot}9) \text{ inches, on the scale used.}$$

With $\sigma = 0{\cdot}3$, this gives $p_2 - p_1 = 8{\cdot}3$ per cent. of the chord (30·5 inches). Again from (5),

$$q_2 - q_1 = \frac{\sigma r}{1+\sigma}(0{\cdot}045) \text{ inches, on the scale used.}$$

Taking $\sigma = 0{\cdot}3$, this gives $q_2 - q_1 = 0{\cdot}34$ per cent. of the maximum thickness (3 inches). Thus for the particular aerofoil section chosen, there is no appreciable difference between the $y$ co-ordinates of the centre of shear and the centre of least strain, although there is a significant difference in their $x$-co-ordinates. The difference between these two centres, which is extremely small for compact sections, is thus far from negligible for the aerofoil section considered. From general considerations it would be expected that this difference would increase for long thin sections. Thus, to obtain an accurate location of the centre of shear the equations (2), or their equivalent, must be used rather than the simpler equations (1).

Knowing the values of $\chi$, values of $\psi$ may be obtained from (3) and hence values of $\phi$ by using the Cauchy-Riemann equations. Alternatively, values of $\phi$ may be obtained direct by solving (by relaxation methods) the equation $\nabla^2\phi = 0$ with boundary condition $\partial\phi/\partial n = 0$. Equations (1) and (2) can then be used to obtain numerically the co-ordinates of the centres of shear and least strain.

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# *A Note on the Problem of Aileron Reversal at Transonic Speeds*


by

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THE PROBLEM of aileron effectiveness when the elastic properties of the wing structure are taken into account has already been adequately covered in the subsonic regime by A. R. Collar and E. G. Broadbent[1]. The method used depends upon strip theory which presupposes a knowledge of the relevant aerodynamic derivatives. A unified method has been considered by the present author[2] which employs either the semi-empirical theory of D. Küchemann[3] or the lifting surface theory of H. Multhopp[4] in such a manner that the effective values of the relevant derivatives are found, together with the rolling efficiency.

In the supersonic regime less has been done, although G. N. Lance[5] has considered a method of superposition of conical fields in the solution of this problem. All these methods depend primarily upon a linearised aerodynamic theory which remains in doubt in the transonic speed range. Rather anomalous behaviour has already been demonstrated at these speeds by ground-launched rockets and tunnel tests[6] and it is questionable whether

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any aerodynamic theory which fails to take into account the occurrence of small local shocks over the wing profile will be able to predict such effects. The importance of these results lies in the fact that, given a configuration of the type used in the test, no wing structure will be so stiff as to prevent the reversal of control in this speed range, since reversal can occur for a rigid structure.

Working on the assumption that it is possible to produce a design which does not demonstrate these adverse features if rigid, it now becomes necessary to determine what structural stiffness is required to prevent aeroelastic (as opposed to aerodynamic) reversal in this speed range. A tentative method is presented here which depends upon the use of strip theory in the manner of E. G. Broadbent[7] and the calculation of the lift distribution in the transonic range for wings in roll as suggested by K. W. Mangler[8]. It is necessary in this method to assume that the load induced on the wing by the aileron is of rectangular distribution and confined to that section of the wing which includes the aileron. The method reduces to the determination of the aileron load centre of pressure (C.P.) locus necessary to induce reversal for the given wing stiffness, which is regarded as adequate if the necessary C.P. locus can be considered as unobtainable.

To facilitate the elastic part of the problem, use is made of the isoclinic locus, which is defined as the locus of points such that if a load be placed on a given point of it, then the consequent distortion of the wing introduces no incidence change on the chord through that point.

## 1. AILERON REVERSAL CRITERION IN THE TRANSONIC CASE: THEORY

In the general case of an aircraft in roll, the distributed wing loading may most conveniently be regarded as a series of point loads on the mainplane isoclinic locus, together with pitching moments about it. This load distribution may be considered as due to three factors, the wing distortion, the rate of roll and the aileron deflection. Accordingly the following definitions are used:—

$L_\theta$ = spanwise load distribution due to distortion, for unit twist ($\theta$) at some reference section

$L_y$ = spanwise load distribution due to rolling, per unit value of $p/V$ where $p$ is the angular velocity and $V$ the speed of flight

$L_\xi$ = spanwise load distribution due to unit aileron angle ($\xi$)

with similarly $M_\theta$, $M_y$ and $M_\xi$ for the nose-up pitching moments. Now it will be realised that these quantities so defined are continuous functions of the spanwise coordinate $y$. To determine the equilibrium condition,

$$\int_0^{b/2} y\left(\theta_0 L_\theta + \frac{p}{V} L_y + \xi L_\xi\right) dy = 0$$

where $b$ is the span, it is more convenient to adopt a strip-theory approach and to consider not a continuous load distribution but a series of finite loads due to small strips of width $\delta y$. To this end, row and column matrices are used for the form

$$\{L\} = \begin{bmatrix} l_1 \delta y_1 \\ \cdot \\ \cdot \\ \cdot \\ l_n \delta y_n \end{bmatrix}; \qquad \|y\| = [y_1, \ldots, y_n]$$

where hereafter { } and ‖ ‖ will be taken to mean column and row matrices.

It thus follows that the two basic definitions necessary to this treatment are

$$\{L\} = \{L_\theta\}\,\theta_0 + \{L_y\}\,\frac{p}{V} + \{L_\xi\}\,\xi \quad . \quad (1)$$

$$\{M\} = \{M_\theta\}\,\theta_0 + \{M_y\}\,\frac{p}{V} + \{M_\xi\}\,\xi \quad . \quad (2)$$

The condition for steady roll on the deformable aircraft is

$$\|y\|\left(\{L_\theta\}\,\theta_0 + \{L_y\}\,\frac{p}{V} + \{L_\xi\}\,\xi\right) = 0, \quad . \quad (3)$$

the corresponding result for the rigid aircraft being

$$\|y\|\left(\{L_y\}\,\frac{p_r}{V} + \{L_\xi\}\,\xi\right) = 0 \quad . \quad . \quad (4)$$

where the suffix "r" here refers to the rigid case. If now it be assumed that distortion does not affect the intrinsic $L_y$ and $L_\xi$ distribution, defining $Y$ by

$$\frac{p}{p_r} = Y \leqslant 1, \quad . \quad . \quad . \quad (5)$$

it follows that

$$\frac{p}{YV} = -\frac{\|y\|\{L_\xi\}\,\xi}{\|y\|\{L_y\}}.$$

Since from (3)

$$\theta_0 = -\frac{\|y\|\left(\{L_y\}\,\frac{p}{V} + \{L_\xi\}\,\xi\right)}{\|y\|\{L_\theta\}},$$

then

$$\theta_0 = \frac{\|y\|\{L_\xi\}\,\xi(Y-1)}{\|y\|\{L_\theta\}}. \quad . \quad . \quad (6)$$

It is now necessary to make the following definitions:—

$$A = \frac{\|y\|\{L_\xi\}}{\|y\|\{L_y\}} \quad . \quad . \quad . \quad (7)$$

$$B = \frac{\|y\|\{L_\xi\}}{\|y\|\{L_\theta\}} \quad . \quad . \quad . \quad (8)$$

Then it follows that

$$\frac{p}{V} = -YA\xi \quad . \quad . \quad . \quad (9)$$

$$\theta_0 = -(1-Y)B\xi \quad . \quad . \quad . \quad (10)$$

So that

$$\{L\} = -\{L_\theta\}(1-Y)B\xi - \{L_y\}\,YA\xi + \{L_\xi\}\,\xi \quad (11)$$

and

$$\{M\} = -\{M_\theta\}(1-Y)B\xi - \{M_y\}\,YA\xi + \{M_\xi\}\,\xi \quad (12)$$

The next step is the determination of the deformation mode. It is necessary to determine two square matrices of influence terms $\theta_{rs}$ and $\overline{\theta}_{rs}$ defining respectively the twist

at station $r$ due to load and moment at station $s$ on the isoclinic locus. Then if the deformation mode be denoted by $f(y)$ such that unit twist occurs at the reference section

$$\theta_a \{f\} = [\theta_{rs}] \{L\} + [\bar{\theta}_{rs}] \{M\}$$
$$= -(1-Y) B\xi \{f\}$$

$$(1-Y)\{f\} = [\theta_{rs}]\left((1-Y)\{L_\theta\} + \frac{YA}{B}\{L_y\} - \frac{1}{B}\{L_\xi\}\right) -$$
$$+ [\bar{\theta}_{rs}]\left((1-Y)\{M_\theta\} + \frac{YA}{B}\{M_y\} - \frac{1}{B}\{M_\xi\}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

It is most convenient to use a non-dimensional form, with

$$q = \frac{1}{2}\rho V^2$$

$$y = \frac{b}{2}\eta.$$

Then, if dashes denote the non-dimensional form,

$$\left.\begin{aligned}
\{L_\theta\} &= qc_r \frac{b}{2}\{L_\theta'\} \qquad \text{where } \{L_\theta'\} = -\left\{a_1 \frac{c}{c_r} f\delta\eta\right\} \\
\{L_y\} &= qc_r\left(\frac{b}{2}\right)^2 \{L_y'\} \text{ where } \{L_y'\} = -\left\{a_1 \frac{c}{c_r}\eta\delta\eta\right\} \\
\{L_\xi\} &= qc_r \frac{b}{2}\{L_\xi'\} \qquad \text{where } \{L_\xi'\} = \left\{a_2 \frac{c}{c_r}\delta\eta\right\} \\
\{M_\theta\} &= qc_r^2 \frac{b}{2}\{M_\theta'\} \qquad \text{where } \{M_\theta'\} = -\left\{ea_1\left(\frac{c}{c_r}\right)^2 f\delta\eta\right\} \\
\{M_y\} &= qc_r^2\left(\frac{b}{2}\right)^2 \{M_y'\} \text{ where } \{M_y'\} = -\left\{ea_1\left(\frac{c}{c_r}\right)^2 \eta\delta\eta\right\} \\
\{M_\xi\} &= qc_r^2 \frac{b}{2}\{M_\xi'\} \qquad \text{where } \{M_\xi'\} = \left\{(ea_2 - m)\left(\frac{c}{c_r}\right)^2 \delta\eta\right\}
\end{aligned}\right\} \quad (14)$$

and $\|y\| = (b/2)\|\eta\|$. (Here $a_1$ = local $(\partial C_L/\partial\alpha)$, $a_2$ = local $(\partial C_L/\partial\xi)$, $m$ = local value of $-(\partial C_m/\partial\xi)$, $ec$ = local distance between C.P. and isoclinic locus, $c_r$ = reference chord.)

Hence $$A = \frac{2}{b}\frac{\|\eta\|\{L_\xi'\}}{\|\eta\|\{L_y'\}}, \qquad B = \frac{\|\eta\|\{L_\xi'\}}{\|\eta\|\{L_\theta'\}}$$

$$\frac{A}{B} = \frac{2}{b}\frac{\|\eta\|\{L_\theta'\}}{\|\eta\|\{L_y'\}} = \frac{2C}{b}, \text{ say.}$$

Then

$$\frac{(1-Y)\{f\}}{qc_r\frac{b}{2}} = [\theta_{rs}]\left((1-Y)\{L_\theta'\} + YC\{L_y'\} - \frac{1}{B}\{L_\xi'\}\right) +$$
$$+ c_r[\bar{\theta}_{rs}]\left((1-Y)\{M_\theta'\} + YC\{M_y'\} - \frac{1}{B}\{M_\xi\}\right) \quad (15)$$

The procedure which is usually adopted with equation (15) is to choose a value of $Y$, assume some arbitrary twist function $f_1$, say, and deduce a second $f_2$. Repeating the process with $f_2$ to find a third mode $f_3$ it will be found that the sequence of modes ultimately converges to some equilibrium state. All this presupposes the knowledge of the derivatives $a_1$, $a_2$ and $m$.

In the absence of derivatives $a_2$ and $m$ it is still possible to develop an approach which indicates the magnitude of these quantities necessary to cause reversal at any given altitude and speed provided that $a_1$ is available, together with the mainplane C.P. locus.

Suppose that the aileron induced load distribution is rectangular and that its local moment about the mainplane C.P. locus is constant. Then it follows that $m = e_1 a_2$, where $e_1$ is some non-dimensional number such that $e_1 c$ is the actual distance between the C.P. of the aileron load and the mainplane C.P.

Also $$\{L_\xi'\} = a_2\left\{\frac{c}{c_r}\delta\eta\right\}$$

where it be understood that the components in the column matrix are zero if the corresponding value of $y$ lies outside the range of values included by the aileron section.

It then follows that

$$\frac{1}{B}\{L_\xi'\} = \frac{\|\eta\|\{L_\theta'\}}{\|\eta\|\left\{\frac{c}{c_r}\delta\eta\right\}}\left\{\frac{c}{c_r}\delta\eta\right\} \quad . \quad (16)$$

where zero elements occur as before.

Similarly

$$\{M_\xi'\} = a_2\left\{(e-e_1)\left(\frac{c}{c_r}\right)^2\delta\eta\right\},$$

so that

$$\frac{1}{B}\{M_\xi'\} = \frac{\|\eta\|\{L_\theta'\}}{\|\eta\|\left\{\frac{c}{c_r}\delta\eta\right\}}\left\{(e-e_1)\left(\frac{c}{c_r}\right)^2\delta\eta\right\}. \quad (17)$$

It thus follows that equation (15) has now been made independent of $a_2$. The only remaining aerodynamic quantity which depends upon the aileron is $(e-e_1)$. Now the number $e$ defines the proportion of the local wing chord which is equal to the distance between corresponding points on the C.P. locus of the mainplane and the isoclinic locus. This number is positive if the C.P. locus is ahead of the isoclinic locus, for it gives a measure of the nose-up pitching moment. Now $m$ is the nose-down pitching moment due to the aileron load, for

$$m = -\frac{\partial C_m}{\partial\xi}.$$

Hence $e_1$ is positive aft of the main C.P. locus.

When considering reversal at some given altitude and speed it follows that $Y = 0$ in the limiting case and that $qc_r b/2$ is known numerically, say, $N$.

Then equation (15) becomes

$$\frac{\{f\}}{N} = [\theta_{rs}]\left(\{L_\theta'\} - \frac{\|\eta\|\{L_\theta'\}}{\|\eta\|\left\{\frac{c}{c_r}\delta\eta\right\}}\left\{\frac{c}{c_r}\delta\eta\right\}\right) +$$
$$+ c_r[\bar{\theta}_{rs}]\left(\{M_\theta'\} - \frac{\|\eta\|\{L_\theta'\}}{\|\eta\|\left\{\frac{c}{c_r}\delta\eta\right\}}\left\{(e-e_1)\left(\frac{c}{c_r}\right)^2\delta\eta\right\}\right).$$

Now it is convenient to write

$$[\theta_{rs}]\{L_\theta'\} = -[a_{rs}]\{f\}, \quad . \quad . \quad (18)$$

where $$a_{rs} = \left(a_1\left(\frac{c}{c_r}\right)\delta\eta\right)_s \theta_{rs} \quad . \quad . \quad (19)$$

*i.e.* the 5th column in $[\theta_{rs}]$ is multiplied by the coefficient of $f_s$ in the column matrix $\{L_\theta'\}$.

Similarly

$$c_r[\bar{\theta}_{rs}]\{M_\theta'\} = -[b_{rs}]\{f\} \quad . \quad . \quad (20)$$

where

$$b_{rs} = c_r\left(ea_1\left(\frac{c}{c_r}\right)^2\delta\eta\right)_s\bar{\theta}_{rs} \quad . \quad . \quad (21)$$

Secondly, having regard to the fact that the only non-zero elements which occur in $\{(c/c_r)\delta\eta\}$ and $\{(e-e_1)(c/c_r)^2\delta\eta\}$ correspond to sections included by the aileron, it is possible to evaluate once for all the products $\|\eta\|\{(c/c_r)\delta\eta\}$ and $[\theta_{rs}]\{(c/c_r)\delta\eta\}$. Similarly if $e_1$ is so chosen as to give a C.P. locus on the half-chord locus of the aileron, the vector $\{(e-e_1)(c/c_r)^2\delta\eta\}$ is completely defined, so that if

$$\|\eta\|\left\{\frac{c}{c_r}\delta\eta\right\} = S \quad . \quad . \quad . \quad (22)$$

$$\frac{1}{S}[\theta_{rs}]\left\{\frac{c}{c_r}\delta\eta\right\} = \{m\} \quad . \quad . \quad (23)$$

$$\frac{1}{S}c_r[\bar{\theta}_{rs}]\left\{(e-e_1)\left(\frac{c}{c_r}\right)^2\delta\eta\right\} = \{n\}. \quad . \quad (24)$$

it follows that

$$\frac{\{f\}}{N} = -\Big([a_{rs}]+[b_{rs}]\Big)\{f\} - \|\eta\|\{L_\theta'\}\Big(\{m\}+\{n\}\Big) \quad (25)$$

These equations, being homogeneous in $f_r$, do not in general have a non-trivial solution. If, however, an arbitrary factor $\lambda$ be applied to $\{n\}$ this corresponds to a shift of amount $(1-\lambda)(e-e_1)c$ to the C.P. locus of the aileron load and a value or values of $\lambda$ may be found which lead to a non-trivial solution.

It is convenient to write

$$\|\eta\|\{L_\theta'\} = -\|\eta^*\|\{f\} \quad . \quad . \quad (26)$$

where

$$\eta_r^* = \left(a_1\left(\frac{c}{c_r}\right)\delta\eta\right)_r\eta_{rs} \quad . \quad . \quad (27)$$

so that the final equations for solution are

$$\frac{\{f\}}{N} = -[a_{rs}+b_{rs}]\{f\} + \|\eta^*\|\{f\}\Big(\{m\}+\lambda\{n\}\Big) \quad (28)$$

Whence $\lambda$ and $\{f\}$ can be found for given $[a_{rs}+b_{rs}]$ and $N$ so that on factoring $[a_{rs}+b_{rs}]$ inversely proportional to the skin thickness it is possible to obtain a range of corresponding values of $\lambda$ and hence a range of C.P. loci for given skins. It is then possible to eliminate those skins for which the C.P. loci are in the region of physical possibility.

It is important to note the sign convention chosen. The load vector due to twist has been defined as

$$\{L_\theta'\} = -\left\{a_1\left(\frac{c}{c_r}\right)f\delta\eta\right\}.$$

This implies that for positive values of $f$ the load is downwards. Hence it follows that $f$ denotes the nose-down incidence. But if $[\theta_{rs}]$ and $[\bar{\theta}_{rs}]$ are defined as the nose-up incidence matrices then equation (28) must be written

$$-\frac{\{f\}}{N} = -[a_{rs}+b_{rs}]\{f\} + \|\eta^*\|\{f\}\Big(\{m\}+\lambda\{n\}\Big) \quad (29)$$

It should be observed that the system of linear homogeneous equations in the variables $\{f\}$ resembles the characteristic root problem, but only superficially so, for on consideration of the determinant of the coefficients, $\lambda$ occurs only to the first power. Hence there exists one, and only one, solution of $\lambda$ giving the reversal condition.

The solution of equation (28) or (29) is best obtained iteratively. That is to say, on guessing a root vector the right hand side of equation (28) may be evaluated to the extent of an arbitrary constant $\lambda$. On comparing the coefficients of the twists in the reference section, $\lambda$ has to be chosen such that it gives the coefficient $1/N$. Hence the complete vector can be obtained. On repeating the process it will be found that the set of vectors and the set of values $\lambda$ converge to their respective limits.

A variation of this system of equations is obtained if it is required to factor $e_1$ rather than $(e-e_1)$. Referring to equation (24), it may be written

$$\frac{1}{S}c_r[\bar{\theta}_{rs}]\left\{(e-e_1)\left(\frac{c}{c_r}\right)^2\delta\eta\right\} = \frac{1}{S}c_r[\bar{\theta}_{rs}]\left\{e\left(\frac{c}{c_r}\right)^2\delta\eta\right\} - \frac{1}{S}c_r[\bar{\theta}_{rs}]\left\{e_1\left(\frac{c}{c_r}\right)^2\delta\eta\right\} = \{n_1\}-\{n_2\}.$$

It then becomes necessary to find $\lambda$ such that

$$\pm\frac{N}{\{f\}} = -[a_{rs}+b_{rs}]\{f\} + \|\eta^*\|\{f\}\Big(\{m\}+\{n_1\}-\lambda\{n_2\}\Big) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

This system of equations may be found necessary if the isoclinic locus is not sensibly parallel to the aileron hinge line in that interval of semi-span.

It should be noticed that the only aerodynamic quantities required in this problem are now $a_1$ and $e$. To obtain them in the transonic range use is made of Ref. 8 to calculate the load density distribution, which yields these quantities on integration.

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FIGURE

Receive

# *The Elimination of Wall Effects in Axial-Flow Compressor Stages*

by

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COMPRESSOR stages are usually designed on the assumption that the gas velocity is nowhere affected by the friction at the walls. The only way in which viscosity is taken into account is in the assumed efficiency, and in a guessed "work-done factor," which ensures that by aiming high the required work is actually attained.

It is known that the radial profile of the axial velocity component becomes more and more peaked through successive stages of a compressor, so that the assumptions just quoted become very inaccurate. It is possible that the efficiency of a stage could be raised considerably if the axial velocity profile were controlled; moreover up to 20 per cent. more work could be done if a "work-done factor" did not have to be applied.

A design method is explained here which uses the tendency of the gas to reach radial equilibrium, to counteract the peaking of the axial velocity component due to friction at the walls. The method demands a foreknowledge of the boundary layers which would be set up in the first stage of a compressor, but once found this would apply to all stages (with perhaps some small correction for hub/tip ratio).

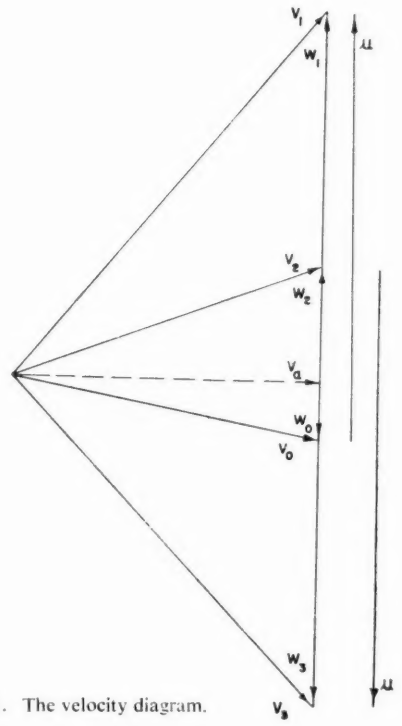


FIGURE 1. The velocity diagram.

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## 1. THE DESIGN OF A SINGLE STAGE: THE TANGENTIAL VELOCITY COMPONENTS, $w$

The first step in the design of a stage is to write down the equations for the required tangential velocity components, which are, to begin with, independent of the axial velocity profile. It is assumed that there is no radial velocity component, although it will be shown later that one will appear if the blade rows are not very closely spaced.

It is convenient to represent the radial co-ordinate $r$ at any cross section in a dimensionless form, such that the value $r=1$ corresponds to the arithmetic mean radius of the annulus. The blade tangential velocity $u$, and the gas axial velocity component $v_a$ corresponding to this mean radius will be written as $\bar{u}$ and $\bar{v}_a$. A typical velocity vector diagram at one radius of a single stage is shown in Fig. 1. It is clear that

$$w_0 + w_1 = w_2 + w_3 = u = \bar{u}r \quad . \quad . \quad (1)$$

If $C_p$ is the specific heat and $\Delta T$ the temperature rise, the work done at any radius is $C_p\Delta T$; this is equal to the rate of change of angular momentum of a unit mass of gas. Hence

$$C_p\Delta T = u(w_1 - w_2) \quad . \quad . \quad (2)$$

But the circulation is

$$\Gamma = s(w_1 - w_2)$$

where $s$ is the blade spacing at any radius; and in dimensionless form, if there are $B$ blades,

$$s = 2\pi r/B .$$

Therefore

$$C_p\Delta T = \bar{u}\Gamma B/(2\pi)$$

and the work done is proportional to the circulation. It is necessary for maximum efficiency to make the circulation (and hence the work) independent of the radius and this will be assumed hereafter, although it is not an invariable design rule.

Note that the circulation does not depend on the blade chord, as with an aircraft wing. Therefore blades with constant chord are not inherently more efficient, as sometimes supposed, and are undesirable in rotors because of their high centrifugal root stress.

From equations (1) and (2),

$$\left.\begin{aligned} w_0 + w_2 &= u - \frac{C_p\Delta T}{u} \\ w_1 + w_3 &= u + \frac{C_p\Delta T}{u} \end{aligned}\right\} \quad . \quad . \quad (3)$$

The dimensionless parameter $R$ (the "reaction") is now introduced such that

$$\left.\begin{aligned} R &= \frac{w_1 + w_2}{2u} \\ \text{and} \qquad 1 - R &= \frac{w_3 + w_0}{2u} \end{aligned}\right\} \quad . \quad . \quad . \quad (4)$$

It may easily be verified that equations (3) and (4) are satisfied by

$$\left.\begin{aligned} w_0 &= (1-R)\,u - \frac{C_p \Delta T}{2u} \\ w_3 &= (1-R)\,u + \frac{C_p \Delta T}{2u} \end{aligned}\right\} \quad . \quad . \quad (5)$$

while $w_1$ and $w_2$ follow from equation (1).

Now $R$ is an arbitrary function of the radius, and so, without loss of generality, it can be expressed as

$$1 - R = \lambda \frac{f(r)}{r}$$

where $f(r)=1$ when $r=1$. Thus $(1-\lambda)$ is the mean radius value of the reaction; and when $f(r)=r$ the reaction is independent of the radius. Equations (5) now become

$$\left.\begin{aligned} w_0 &= \lambda \bar{u} f(r) - \frac{C_p \Delta T}{2\bar{u} r} \\ w_3 &= \lambda \bar{u} f(r) + \frac{C_p \Delta T}{2\bar{u} r} \end{aligned}\right\} \quad . \quad . \quad (6)$$

## 2. THE DESIGN OF A SINGLE STAGE: THE AXIAL VELOCITY COMPONENT $v_a$

Calculation of the axial velocity component after each row of blades in a stage requires the solution of the equations of motion, but this is only possible if certain simplifying assumptions are made. It will be assumed here that the flow is steady, incompressible, and inviscid; and that at the plane considered there is radial equilibrium, which implies that the streamlines are parallel. The equation of motion is then simply

$$\frac{\rho w^2}{r} = \frac{dp}{dr} \quad . \quad . \quad . \quad (7)$$

where $p$ and $\rho$ are the local pressure and density.

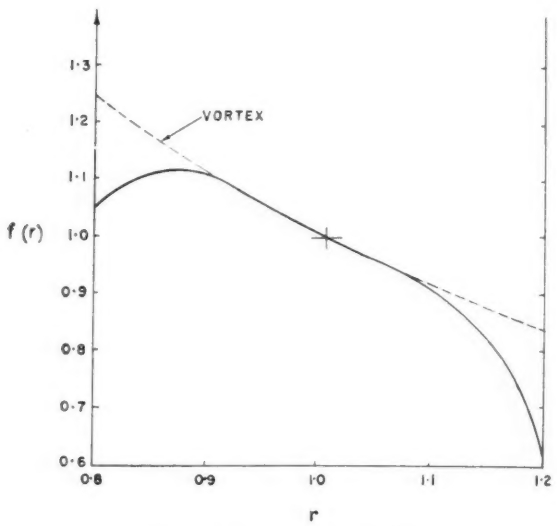


FIGURE 2. The reaction function.

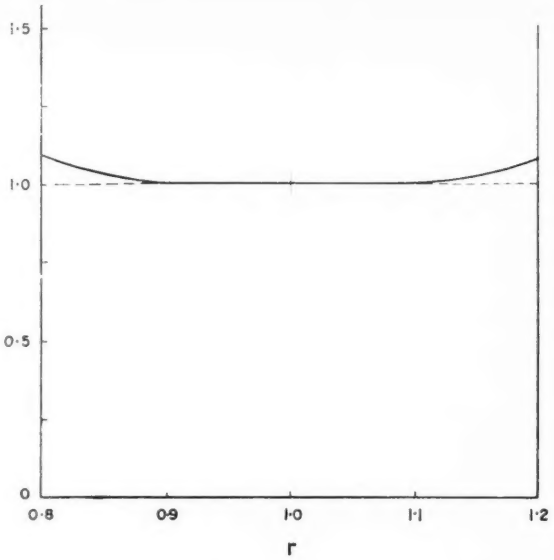


FIGURE 3. The axial velocity profile.

The stage is assumed to have no radial variation of energy, that is

$$\frac{\partial}{\partial r}\left[\frac{p}{\rho} + \frac{1}{2}(w^2 + v_a^2)\right] = 0$$

or

$$\frac{1}{\rho}\frac{\partial p}{\partial r} + w\frac{\partial w}{\partial r} + v_a \frac{\partial v_a}{\partial r} = 0 \quad . \quad . \quad . \quad (8)$$

From equations (7) and (8) the basic equation of radial equilibrium is obtained:—

$$-v_a \frac{\partial v_a}{\partial r} = \frac{w^2}{r} + w\frac{\partial w}{\partial r} \quad . \quad . \quad (9)$$

from which the axial velocity distributions (with radius) can be calculated for a given set of tangential velocities. On the other hand if the required axial velocity profiles are known, the tangential velocities can be arranged so as to give them.

Substituting in equation (9) from equation (6) gives

$$-v_a \frac{\partial v_a}{\partial r} = \lambda \bar{u} \left\{ \lambda \bar{u} f(r) \mp \frac{C_p \Delta T}{2\bar{u} r} \right\} \left\{ \frac{f(r)}{r} + f'(r) \right\} \quad (10)$$

The axial velocity component is constant with radius, therefore, if either $\lambda=0$, or $f(r)=1/r$. In the latter case, it may be seen from equations (6) that $w_0$ and $w_3$ are proportional to $1/r$, and form vortices about the axis.

Equation (10) implies that equilibrium before and after the rotor blade row requires in general a change of axial velocity profile, and hence a radial velocity component, which may be quite large. It is known from experiment, however, that the streamlines downstream of a blade row do not become parallel until a distance of the order of one blade height. And as blade rows in compressors are spaced much closer than this, the gas has no room to take up the final equilibrium profile. Results nearer the truth are likely to be given by the opposite assumption, namely that the blade rows are so closely spaced that the axial velocity profile is

unchanged across the row, and no radial velocity component is created. So the variable term in equations (10) may be eliminated to give simply

$$-v_a\frac{\partial v_a}{\partial r}=\lambda^2\bar{u}^2 f(r)\left\{\frac{f(r)}{r}+f'(r)\right\}.$$

Integration gives

$$-\frac{(v_a^2-\bar{v}_a^2)}{\lambda^2\bar{u}^2}=\{f^2(r)-1\}+2\int_1^r f^2(r)\frac{dr}{r} \quad . \quad (11)$$

Hence for a prescribed function $f(r)$ the tangential velocities are calculated from equations (6) and the (inviscid) axial velocity profile from equation (11). Simple examples of the function are

(*a*) The vortex flow $f(r)=1/r$, which gives $v_a=\bar{v}_a$ everywhere.

(*b*) Constant reaction, $f(r)=r$, giving
$$v_a^2-\bar{v}_a^2=-2\lambda^2\bar{u}^2(r^2-1).$$

(*c*) $f(r)=1$, giving
$$v_a^2-\bar{v}_a^2=-2\lambda^2\bar{u}^2\log_e r.$$

(*d*) $f(r)=r$, giving
$$v_a^2-\bar{v}_a^2=-3\lambda^2\bar{u}^2(r-1).$$

(*e*) $f(r)=r+\dfrac{C_p\Delta T/(2\lambda\bar{u}^2)}{r}$ ("wheel plus vortex").

To establish the scale of the axial velocity profile, $\bar{v}_a$ must be determined in terms of the known mean axial velocity $(v_a)_m$. This is found from the equation of continuity

$$\int v_a r\,dr=(v_a)_m\int r\,dr,$$

which can easily be solved graphically. In many cases the difference between $\bar{v}_a$ and $(v_a)_m$ is negligible.

## 3. DESIGN METHOD FOR A PRESCRIBED AXIAL VELOCITY PROFILE

If, however, it is desired to choose $f(r)$, and hence the tangential velocities, in order to give a particular axial velocity profile, the nature of equation (11) forces a trial and error solution, although it is not laborious. The case of most practical interest is a design which increases the theoretical value of the axial velocity at the walls, so as to counteract the reduction of velocity there due to friction. The boundary layer is thus controlled by the radial pressure gradient; although no radial flow actually takes place, nor is there a loss of efficiency due to the creation of secondary vortices.

An example will best illustrate the method, so consider a stage with the following properties:—

$$\text{Hub/tip ratio}=2/3;\ \lambda=\tfrac{1}{2};\ \bar{u}/\bar{v}_a=\sqrt{2};$$
$$C_p\Delta T/(\tfrac{1}{2}\bar{u}^2)=1/\sqrt{2}.$$

Then equations (6) become

$$\left.\begin{aligned}\frac{w_0}{\bar{v}_a}&=\frac{f(r)}{\sqrt{2}}-\frac{1}{4r}\\ \frac{w_1}{\bar{v}_a}&=\frac{f(r)}{\sqrt{2}}+\frac{1}{4r}\end{aligned}\right\} \quad . \quad . \quad . \quad (12)$$

If $f(r)=1/r$, the foregoing inviscid theory gives a flat axial profile. Now suppose that when the stage is built the friction at the walls reduces the axial velocity by about 10 per cent., near the walls. Then the stage can be redesigned, by choosing $f(r)$ appropriately, to make the theoretical velocity increase by 10 per cent. near the walls. The net effect should be zero.

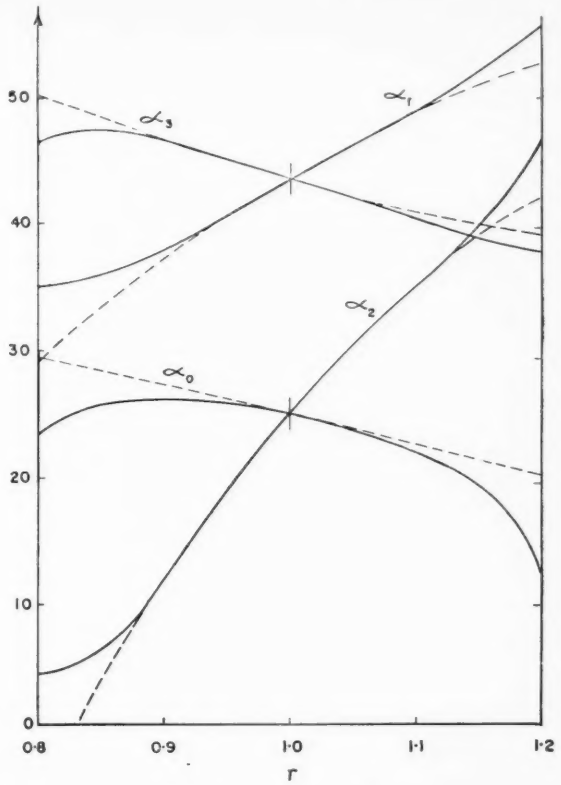


FIGURE 4. The gas angles.

If the function shown in Fig. 2 is chosen, numerical solution of equation (11) gives the velocity profile of Fig. 3. The gas angles are then calculated, *assuming a flat profile*, and are compared, in Fig. 4, with the angles for inviscid flow.

## 4. DISCUSSION OF PREVIOUS SUGGESTIONS

The design method given here differs from two previous suggestions which have been made. These were

(*a*) To design each stage of a compressor to produce constant circulation with the peaked profile it was known (by experiment) to receive. The method requires foreknowledge of the profile which is set up in *each* stage of a compressor, and assumes that this profile will be unchanged when different blading is put in.

(*b*) To control the axial velocity profile through a compressor by increasing the circulation of each stage near the walls ("energising the boundary layer"). This aim would be achieved only at the expense of efficiency because of the large secondary vorticity associated with strongly varying circulation.

# *Stresses and Deflection in a Flat Plate with Clamped Edges under Normal Pressure*

by

J. K. OAKS, B.Sc., A.M.I.Mech.E.

*(Royal Aircraft Establishment)*

TESTS were made at the request of the Royal Aeronautical Society Structures Committee to extend the information on Data Sheet 02.09.02 from a value of the parameter.

$$\frac{p}{E}\left(\frac{b}{t}\right)^4 \text{ of 500 up to 3,000.}$$

NOTATION

$p$ = normal pressure (lb./in.$^2$)
$E$ = Young's modulus = $10 \times 10^6$ lb./in.$^2$
$\mu$ = Poisson's ratio = 0·3
$b$ = length of short side of plate = 36 in.
$t$ = thickness of plate = 0·125 in.
$f_1$ = maximum tension stress at centre of plate (lb./in.$^2$)
$f_2$ = maximum tension stress at edge of plate (lb./in.$^2$)
$f_3$ = maximum tension stress in median plane (lb./in.$^2$)
$\delta$ = deflection (in.)

## 1. THE TEST RIG

The essentials of the test rig are:—

(*i*) That the plate should be really flat.

(*ii*) That the true stress free position for the plate should be determined, because near the flat state large stress and deflection changes occur for small load changes.

(*iii*) The edges of the plate should be as fixed as possible. The difficulty of this increases with the size of the plate, and a large plate is desirable because the stress can then be measured relatively closer to the edge.

A steel box for the tests was supplied by Saunders-Roe. Its internal dimensions were 36 in. × 40 in. A light alloy D.T.D.546 10-gauge plate was made to suit. The edges of the plate were reinforced by gluing on two-inch wide 6-gauge light alloy strips with hot setting Araldite. The plate was then flattened by beating and tested for flatness on a surface table. Strain gauges were attached and the plate was bolted to the box by $\frac{3}{8}$ in. bolts at $1\frac{1}{2}$ in. pitch. A section of the edge is shown in Fig. 1. The box was made from four 6 in. × 3 in. channels welded at the corners. The webs of the long sides were stiffened 15 in. from each end by welded plates. The base was a $\frac{1}{4}$ in. thick plate. Two 4 in. × 2 in. channels, the width of the box, were bolted under the base plate in line with the webs. The box was stiffened inside by channels wedged in place as in Fig. 2. With the test plate bolted down and sufficient pressure applied to support the weight of the plate it was flat to within a few thousands of an inch as measured with a straight edge and feeler gauges. Separate holes were provided in the box for the air inlet, the water manometer and the strain gauge wires.

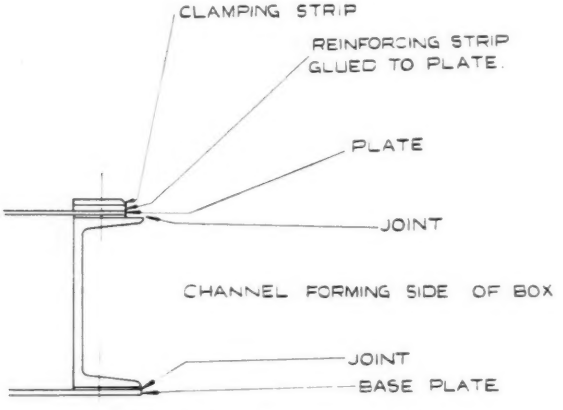


FIGURE 1. Section through edge of box.

*Received 13th March 1953.*

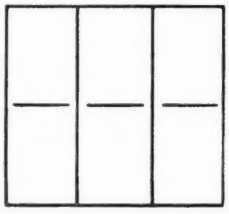

FIGURE 2. Plan showing channels inside box.

The plate was loaded by air pressure from compressed air mains or alternatively by a vacuum pump coupled to the box through a reservoir vessel. Pressure was controlled by a leak valve. The deflection at the centre of the plate was measured by a 1/1,000 in. dial indicator. It was fixed to a bridge running across and fixed to the sides of the box.

The stress-free position for the plate was determined by measuring the deflections at small increments of pressure from −10 to +10 in. of water and finding the point of symmetry on the curve Fig. 3. This was at +0·4 in. of water which was taken as datum in the subsequent tests.

The edge fixity of the plate was measured optically. Small concave mirrors of two metres radius were attached to the plate near the edge. A Pointolite lamp and a sheet of paper on a board were fixed two metres above the plate and parallel to it. The reflections of the lamp from the mirrors were traced on the paper: the movements of the light spots were measured: and hence the angular movement of the plate was calculated. The results plotted in Fig. 4 indicate that the plate is effectively fixed 0·2 in. outside of the actual edge.

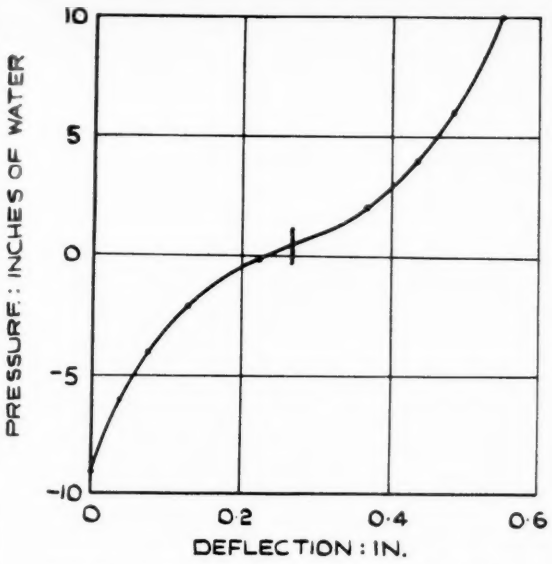


FIGURE 3. Curve of pressure against central deflection, to find point of symmetry.

2. THE STRAIN GAUGES

The gauges were fixed along a line joining the centres of the long sides. The distances from the edge to the centre of the gauge element are given in Table I. Numbers 11 and 21 to 25 are measured from one edge, the remainder from the other.

Gauges from the same batches were calibrated before use on a strip of the plate material loaded in tension at the same time as the Young's modulus and Poisson's ratio were determined. The gauge factor for the standard gauges was 2·0 and for the small gauges 1·4.

The percentage change of resistance of the gauges was read on a 50-way strain-gauge measuring instrument.

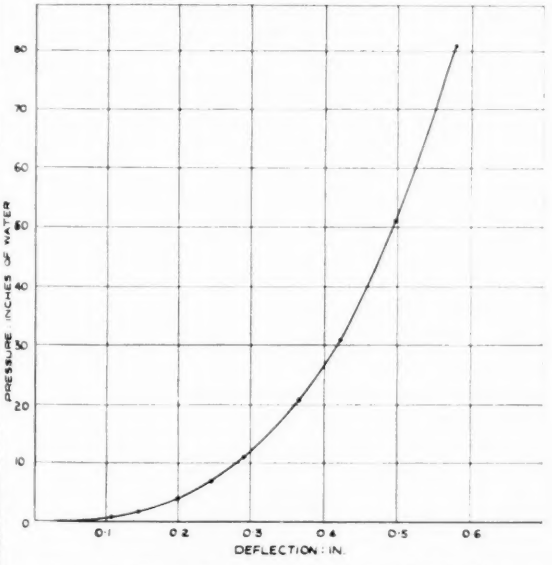


FIGURE 5. Curve of pressure against central deflection.

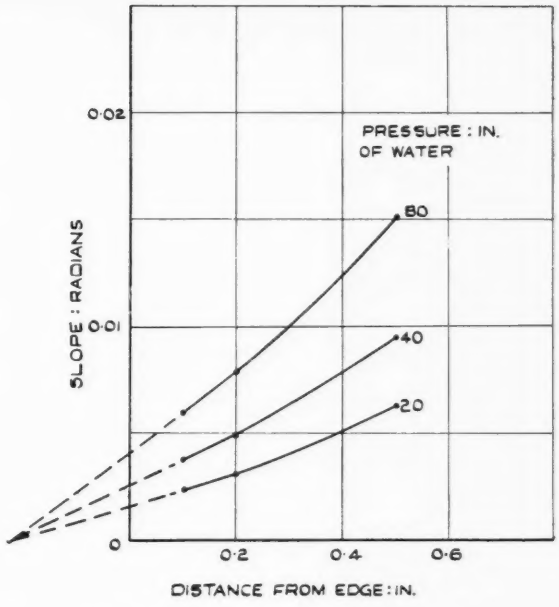


FIGURE 4. Slope of plate near edge, to measure edge fixity.

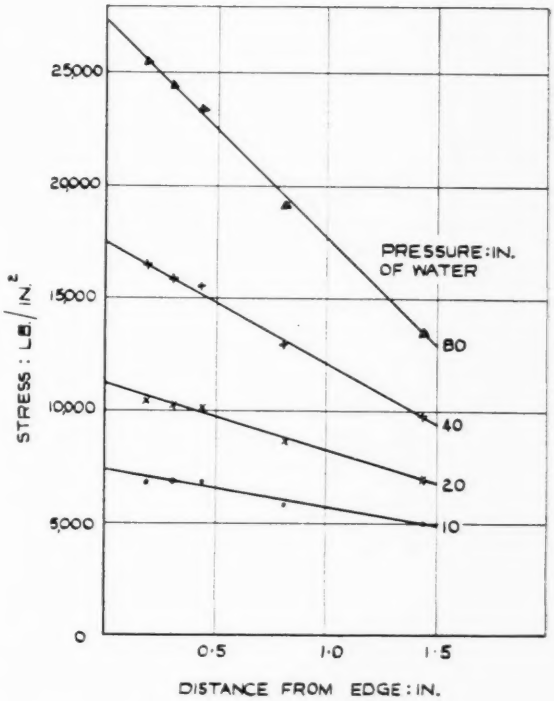


FIGURE 6. Stress distribution across the plate at a pressure of 80 inches of water.

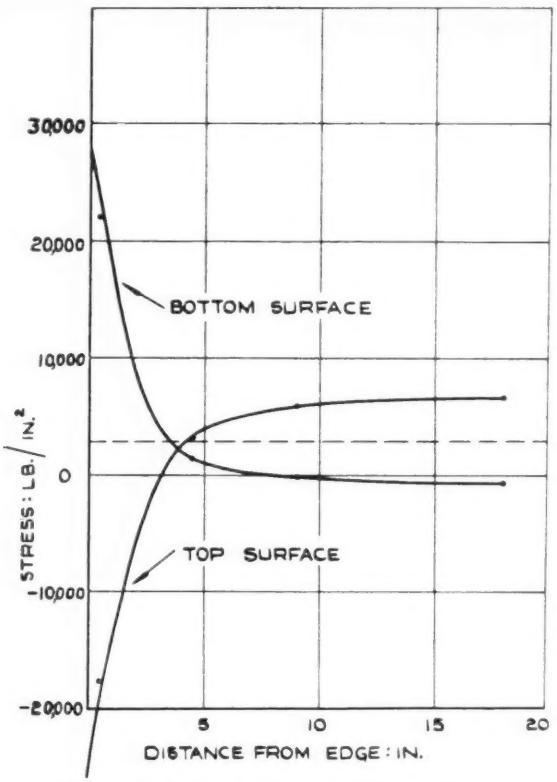


FIGURE 7. Stresses on bottom surface near edge.

## 3. RESULTS

Pressure was applied in increments and the deflection and strains were plotted against pressure. The deflection curve is shown in Fig. 5. At selected pressures the strains were read off from the curves and the corresponding stresses were plotted against the distance from the edge of the plate. A typical curve is shown in Fig. 6. The stress at the edge $f_2$ was determined from the separate curve (Fig. 7) of stresses from the small gauges Numbers 21 to 25. The stress $f_1$ was taken from the centre top gauges Numbers 12 and 13. The stress $f_3$ was the mean of pairs of top and bottom gauges, excluding the edge gauges as these involved the

TABLE I

| *Element length in.* | *Distance from edge in.* | *Gauge number* Bottom surface Longitudinal | Top surface Longitudinal | Bottom surface Transverse* | Top surface Transverse* |
|---|---|---|---|---|---|
| $\frac{1}{2}$ | 0·4 | 8 | 11, 18 | 9 | 19 |
| | 4·5 | 6 | 16 | 7 | 17 |
| | 9 | 4 | 14 | 5 | 15 |
| | 18 | 2 | 12 | 3 | 13 |
| $\frac{1}{8}$ | 0·2 | 21 | | | |
| | 0·3 | 22* | | | |
| | 0·45 | 23* | | | |
| | 0·8 | 24 | | | |
| | 1·45 | 25 | | | |

*Transverse gauges and numbers 22 and 23 were displaced a little to one side or the other to avoid overlapping.

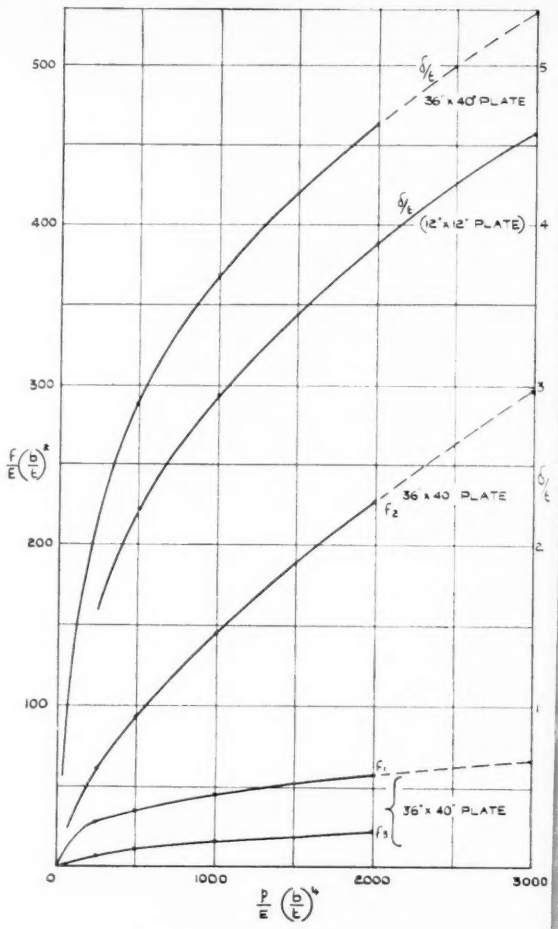


FIGURE 8. Results in data sheet form.

difference of large quantities. The final curves are shown in data sheet form in Fig. 8.

The maximum pressure used in the tests was 2·9 lb./in.² which gave a value of

$$\frac{p}{E}\left(\frac{b}{t}\right)^4 = 2{,}000.$$

Higher pressures might have given stresses outside the elastic limit. The curves of pressure against strain and pressure against deflection have been extrapolated fairly reliably because the curves are almost linear beyond the limit of the test.

Figure 8 also shows the deflection curve for a 12 in. × 12 in. × 20 gauge plate; because the loads involved were small it was held rigidly to a box whose sides were two-inch square bars. The smaller deflection will be due in part to its being square instead of rectangular and in part to the rigidity of the edge fixing. It was not considered large enough for strain-gauge measurements.

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THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

# Eighty-Eighth Annual Report of the Council 1952-1953

DURING the year the Society was honoured by Her Majesty Queen Elizabeth II. who graciously consented to become the Patron of the Society.

Although there has been no single item of extraordinary expansion in 1952, the Council feel that there has been a general overall increase in the activity of the Society, which is possibly reflected in the increase in Membership and the founding of New Branches.

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N. E. ROWE, F.R.AE.S.
S. CAMM, F.R.AE.S.
SIR WILLIAM S. FARREN, F.R.AE.S.
W. E. W. PETTER, F.R.AE.S.
SIR HAROLD ROXBEE COX, F.R.AE.S.
W. TYE, F.R.AE.S.

## Representatives on Other Bodies

*General Board of the National Physical Laboratory*: Sir Frederick Handley Page and Major G. P. Bulman.

*Executive Board of the National Physical Laboratory*: Sir Arthur Gouge.

*Royal Society*—National Committee for Theoretical and Applied Mechanics: Mr. A. A. Hall.

*Institution of Electrical Engineers*—Committee on Regulations for the Electrical Equipment of Aircraft: Mr. C. G. A. Woodford.

*Institution of Electrical Engineers*—Committee on Radio Equipment for Civil Aircraft: Mr. C. H. Jackson.

*Institution of Mechanical Engineers*—National Certificates and Diplomas in Mechanical Engineering: Mr. R. Tatham.

*Engineering Joint Council*: Major F. B. Halford.

*Engineering Joint Council*—Special Education Representative: Professor G. T. R. Hill.

*Governing Body of Institute of Technology, Loughborough*: Mr. A. G. Elliott.

*Board of Governors of the R.A.E. Technical College*: Sir William S. Farren.

*College of Aeronautics Board of Governors*: Sir Roy Fedden and Sir Harold Roxbee Cox.

*British Standards Institution—Nomenclature Committee*: Dr. D. M. A. Leggett.

*British Standards Institution*—Units and Symbols Standards Committee: Dr. A. M. Ballantyne and Miss E. C. Pike.

*British Standards Institution*—Aircraft Industry Standards Committee: Mr. H. Knowler and F. M. Owner.

*British Standards Institution*—Jewels and Pivots for Instruments Committee: Major B. W. Shilson.

*British Standards Institution*—Technical Committee M/1: Mr. S. Camm.

*Segrave Trophy Committee*: Major R. H. Mayo.

*City and Guilds of London Institute*—Advisory Committee on Aeronautical Engineering Practice: Sir Roy Fedden, Mr. R. L. Lickley, Mr. B. S. Shenstone and Dr. A. M. Ballantyne.

*City and Guilds of London Institute*—Education Policy Committee: Sir Arthur Gouge.

*Association of Special Libraries and Information Bureaux*: Captain J. L. Pritchard.

*National Central Library*: Captain J. L. Pritchard.

*Regional Advisory Committee for Mechanical Engineering*: Sir John S. Buchanan.

*University of London*—Faculty of Engineering Special Committee: Mr. R. S. Stafford.

*University of London Senate—Board of Studies*: Dr. A. M. Ballantyne.

*Court of University of Bristol*: Dr. A. E. Russell.

## Election of President and Vice-Presidents

G. H. Dowty, F.R.Ae.S., was elected President for 1952-53 and took office at the Eighty-Seventh Annual General Meeting held on 7th May 1952.

At the meeting of Council on 29th May 1952 the following were elected Vice-Presidents:

G. R. Edwards, C.B.E., B.Sc., F.R.Ae.S.

Sir William S. Farren, C.B., M.B.E., M.A., F.R.S., F.R.Ae.S.

P. G. Masefield, M.A., F.R.Ae.S.

## Fellowship of the Society

At the Eighty-Seventh Annual General Meeting, held on 7th May 1952 the following were elected Fellows:

| | |
|---|---|
| F. S. Burt | W. F. Hilton |
| A. V. Cleaver | R. C. Morgan |
| L. G. Fairhurst | H. C. Smith |
| R. H. T. Harper | R. H. Weir |

## Lectures

During the past year the number of Main Lectures has been reduced to 9, including the British Commonwealth and Wilbur Wright Lectures; three of the Main Lectures have been held at Branches. It is considered that the Section Lectures have proved their worth, and that there is no need therefore to laden the Lecture Programme with Main Lectures. The Main Lectures held at the Branches were:—

Brough Branch—21st February 1952: "Power Steering for Aircraft," K. G. Hancock, B.Sc., A.F.R.Ae.S., and P. Person, M.A., A.F.R.Ae.S.

Luton Branch—24th April 1952: "Fuel Systems for Turbo-Engined Aircraft," J. E. Walker, A.F.R.Ae.S.

Weybridge Branch—12th November 1952: The First R. K. Pierson Memorial Lecture, "Rex Pierson—An Appreciation and the Lessons of his Work," Sir A. H. Roy Fedden, M.B.E., D.Sc., M.I.Mech.E., F.R.S.A., M.S.A.E., F.R.Ae.S. Not only was this Lecture the First R. K. Pierson Memorial Lecture but it was the first Lecture, outside the Main Lectures, to be given a commemorative name. In future it will be given annually as a Branch Lecture.

These Main Lectures at Branches have proved to be very successful. The attendances equal, if not surpass, those at the Lectures in London.

Council wish to record their appreciation of the work done by Mr. N. E. Rowe, Chairman of the Branches Committee, in the furtherance of this idea, and they also appreciate the help of the Industry and Establishments, who have shown the co-operation required to ensure their success.

The following lists the Main Lectures and Section Lectures read before the Society in London in 1952:—

31st January: SECTION LECTURE—"The Problems of Short-Haul Air Transport," P. W. Brooks, B.Sc., A.C.G.I., A.F.R.Ae.S.

7th February: MAIN LECTURE—"The Availability and Use of Aeronautical Information." A Joint Discussion with the Aeronautical Information Group of A.S.L.I.B.

12th February: SECTION LECTURE—"Flight Test Problems for Civil Aircraft," B. P. Laight, B.Sc., A.F.R.Ae.S.

19th February: SECTION LECTURE—"Recent Development in Glider Design," K. G. Wilkinson, B.Sc., D.I.C., A.F.R.Ae.S.

4th March: SECTION LECTURE—"Bogie Undercarriages," R. C. Cussons, D.F.C., M.A., A.F.R.Ae.S.

20th March: MAIN LECTURE—"The Spacing of Aircraft Under High Density Approach Conditions," E. A. Whiteley, D.F.C., B.A., A.F.R.Ae.S.

27th March: SECTION LECTURE—"Some Aspects of Civil Jet Aircraft," D. R. Newman, A.F.R.Ae.S.

29th May: MAIN LECTURE—The Fortieth Wilbur Wright Memorial Lecture: "Prophecy and Achievement in Aeronautics," Sir Harry M. Garner, C.B., M.A., F.R.Ae.S.

2nd October: MAIN LECTURE—The Eighth British Commonwealth and Empire Lecture: "Maintaining Airworthiness in Operation," R. E. Hardingham, O.B.E., F.R.Ae.S.

16th October: SECTION LECTURE—"The Training of Test Pilots," Group Captain A. E. Clouston, D.S.O., D.F.C., A.F.C.

30th October: SECTION LECTURE—"Temperature Control of Jet-Engined Aircraft," E. W. Still, Ph.D., B.Sc., A.C.G.I., F.R.Ae.S.

20th November: SECTION LECTURE—"The Design of a Wind Tunnel Balance," L. E. Leavy, A.F.R.Ae.S. and C. G. Saunders.

27th November: MAIN LECTURE—"The Scope and Limitations of the Photoelastic Method of Stress Analysis," Colonel H. T. Jessop, T.D., M.Sc., F.Inst.P.

4th December: SECTION LECTURE—"Air Traffic Control Today and Tomorrow," Captain V. A. M. Hunt, A.F.R.Ae.S.

## Louis Bleriot Lecture

The Fifth Louis Bleriot Lecture was delivered at the Société des Anciens Elèves Ingénieur Arts et Métiers, Avenue d'Iena, Paris, on 12th March, 1952, by Mr. Henry Knowler, A.M.I.C.E., F.R.Ae.S.

About thirty members of the Society attended the Lecture, and some of them took the opportunity of visiting the Office National d'Etudes et de Recherches Aeronautiques.

(A full Report was published in the May 1952 JOURNAL.)

## Wilbur Wright Memorial Lecture

The 40th Wilbur Wright Memorial Lecture was read on 29th May 1952 at the Institution of Civil Engineers by Sir Harry Garner, K.B.E., C.B., F.R.Ae.S., on "Prophecy and Achievement in Aeronautics."

(A full Report was published in the July 1952 JOURNAL.)

## British Commonwealth and Empire Lecture

The Eighth British Commonwealth and Empire Lecture was delivered on 2nd October 1952 at the Institution of Mechanical Engineers by Mr. R. E. Hardingham, O.B.E., F.R.Ae.S., M.S.L.A.E., on "Maintaining Airworthiness in Operation."

(A full Report was published in the November 1952 JOURNAL.)

## Divisions

At the Dinner honouring Mr. R. E. Hardingham, O.B.E., F.R.Ae.S., who gave the Eighth British Commonwealth and Empire Lecture, for the first time there was a toast to "The Divisions of the Society." The reply to this was given by Mr. J. Nash, A.F.R.Ae.S., the President of the Southern Africa Division. Mr. L. C. Williams, of the Australian Division, was also present. The Council hope that this Toast will be perpetuated.

The absence of aircraft manufacturing firms makes the work of the Divisions of Southern Africa and New Zealand more difficult, but the enthusiasm and effort being shown to counteract this handicap is very gratifying to the Council.

At present the relationship between the Society and the Divisions is under review, for it is felt that it is possible that something might be done to strengthen the ties between them and the Main Society.

It is becoming established that Members of the Divisions, when in this Country, visit the offices of the Society, for there have been frequent visitors during the past year.

The current report of the New Zealand Division is published in this issue and it is hoped from time to time to publish fuller reports of the Divisions' activities in the JOURNAL.

## Branches

The past year has been notable for the foundation of two new Branches, for the first Branch Area Meeting and for the continued success of the Main Society Lectures at Branches.

The two new Branches are Merthyr Tydfil and Henlow, and all reports confirm that if attendance is a measure of success, both are showing signs of being eminently successful.

An Area Meeting was held at Coventry, and at least seven Branches were represented. This was the first to be held, and it augured well for the future.

Two Branch Conferences have been held, and the attendance by Chairmen and Secretaries has been very good. At these meetings are voiced the many suggestions which result in the better functioning of the Branches.

When he was Vice-President, and since he became President, Mr. G. H. Dowty has visited many of the Branches, and he has been very pleased to see the enthusiasm and untiring work done by the Branch Committees.

## Membership

The total Membership of the Society has increased, over the past year, by more than two hundred. There have been increases in every grade. The Council are particularly pleased to note the increase in the number of Students, for this is the first time for some years that such an increase has been recorded.

The table on the opposite page shows, in detail, the Membership on 31st December 1952.

## MEMBERSHIP AT 31st DECEMBER 1952

| Grade | London Register | Australian Division | New Zealand Division | Southern Africa Division | Life and Honorary | Totals | Suspended Members (included in the foregoing figures) |
|---|---|---|---|---|---|---|---|
| Fellows ... ... | 355 (352) | 12 (13) | — (—) | 2 (1) | 50 (52) | 419 (418) | 3 (2) |
| Associate Fellows . | 2821 (2686) | 97 (90) | 28 (27) | 40 (38) | 16 (16) | 3002 (2857) | 73 (83) |
| Associates ... ... | 1948 (1951) | 73 (67) | 58 (50) | 80 (87) | 5 (5) | 2164 (2160) | 131 (139) |
| Graduates ... ... | 1219 (1195) | 48 (41) | 5 (5) | 4 (4) | — (—) | 1276 (1245) | 40 (43) |
| Students ... ... | 748 (714) | 55 (52) | 1 (1) | 8 (2) | — (—) | 812 (769) | 57 (57) |
| Founder Members | 14 (14) | — (—) | — (—) | — (—) | 1 (1) | 15 (15) | — (4) |
| Companions ... | 153 (152) | 6 (6) | 4 (3) | 4 (5) | 12 (11) | 179 (177) | 5 (10) |
| Temporary Honorary Members | — (—) | — (—) | — (—) | — (—) | 47 (43) | 47 (43) | — (—) |
| | 7258 (7064) | 291 (269) | 96 (86) | 138 (137) | 131 (128) | 7914 (7684) | 309 (338) |

Figures in brackets are corresponding figures at 31st December 1951

## Graduates' and Students' Section

The year has been notable for the number of lectures delivered to the Section by Graduates of the Society. The Section has held eight lectures, of which Graduates have given six.

This record is partly the result of the Committee's efforts over the past eighteen months to obtain more lectures by members of the Section. The year has thus seen the fulfilment of one of the Section's primary objectives, which is to provide opportunities for Graduates and Students to deliver lectures and take part in discussions.

Attendance at lectures has been the best for several years. The average attendance being 53 compared with 41 last year.

The Annual Reception held at the Society in October 1952 did much to create an informal and friendly atmosphere. On this occasion the Section had the pleasure of the company of the President and Mrs. Dowty, Mr. and Mrs. Scott Hall, and the Secretary and Mrs. Ballantyne. A series of film shows were shown, dancing took place in the Library and refreshments were served.

## Honours Awarded to Members

The following Members of the Society received awards in 1952:—

NEW YEAR'S HONOURS—JANUARY 1952

| | |
|---|---|
| Knights Bachelor | Professor L. Bairstow (*Honorary Fellow*) |
| | D. R. Pye (*Fellow*) |
| K.B.E. | Air Marshal C. W. Weedon (*Associate Fellow*) |
| | T. W. White (*Companion*) |
| C.B.E. | Air Commodore C. L. Dann (*Associate Fellow*) |
| | Group Captain J. M. Freeman (*Associate*) |
| | H. L. Stevens (*Fellow*) |
| O.B.E. | Wing Commander G. L. Gandy (*Associate*) |
| M.B.E. | J. A. Hamilton (*Graduate*) |
| | Squadron Leader F. A. Houghton (*Associate*) |
| King's Commendation for Valuable Service in the Air | Squadron Leader K. Ritchley (*Associate Fellow*) |

BIRTHDAY HONOURS—JUNE 1952

| | |
|---|---|
| Knights Bachelor | Air Commodore Vernon S. Brown, C.B., O.B.E., M.A., R.A.F.(Ret'd) (*Fellow*) |
| | W. S. Farren, C.B., M.B.E., M.A., F.R.S., (*Fellow*) |
| G.C.M.G. | The Viscount Knollys (*Companion*) |
| C.B.E. | E. C. Bowyer (*Companion*) |
| | G. R. Edwards, M.B.E., B.Sc. (*Fellow*) |
| | H. Sammons (*Fellow*) |
| | H. Sutton, D.Sc. (*Fellow*) |
| O.B.E. | Wing Commander C. A. Pike, A.F.C. (*Associate Fellow*) |
| | G. W. Stallibrass (*Associate*) |
| M.B.E. | G. A. Champniss (*Associate*) |
| | L. C. Skinner (*Associate Fellow*) |
| | A. W. Watkins (*Associate Fellow*) |

NEW YEAR'S HONOURS—JANUARY 1953

| | |
|---|---|
| Knight Bachelor | Harold Roxbee Cox (*Fellow*) |
| C.B. | Air Vice-Marshal H. P. Fraser (*Fellow*) |
| G.B.E. | Lord Brabazon of Tara (*Honorary Fellow*) |
| C.B.E. | Captain K. J. G. Bartlett (*Associate Fellow*) |
| O.B.E. | Squadron Leader N. F. Duke (*Associate*) |
| | Commander B. W. Galpin, R.N.(Retd.) (*Companion*) |

| | |
|---|---|
| M.B.E. | Mrs. A. C. Douglas (*Associate*)<br>D. M. Jameson (*Associate Fellow*) |
| Queen's Commendation for Valuable Service in the Air | Captain A. M. A. Majendie (*Associate Fellow*) |

THE DANIEL GUGGENHEIM MEDAL

Sir Geoffrey de Havilland (*Fellow*) was awarded the Daniel Guggenheim Medal for 1952. The award was made for "forty years of pioneering in military and commercial aircraft and the development of long range jet transport."

INSTITUTION OF MECHANICAL ENGINEERS

Sir David Pye, C.B., M.A., Sc.D., F.R.S. (*Fellow*) was elected President of The Institution of Mechanical Engineers.

Sir Harold Roxbee Cox (*Fellow*) (Past President) was awarded the James Clayton Prize for his contributions to engineering science and practice particularly in the fields of aeronautics, power generation and fuel utilisation.

INSTITUTE OF THE AERONAUTICAL SCIENCES

Professor J. H. Parkin (*Fellow*) was awarded the Honorary Fellowship of The Institute of the Aeronautical Sciences. Only one such award is made in the year to a non-American.

ROYAL SOCIETY

Professor A. G. Pugsley (*Fellow*) and Dr. D. M. Smith (*Fellow*) were awarded the honour of Fellow of The Royal Society.

SOCIETY OF AERONAUTICAL WEIGHT ENGINEERS, INC.

Sir Roy Fedden (*Fellow*), who is a Founder Member of The Society of Aeronautical Weight Engineers, Inc., was elected an Honorary Fellow of that Society.

AERO MEDICAL ASSOCIATION

Dr. Kenneth G. Bergin, M.A., M.D., D.P.A. (*Associate Fellow*), B.O.A.C. Regional Medical Director, was among the ten new Fellows of The Aero Medical Association elected as "having made outstanding contributions to aviation medicine."

HELICOPTER ASSOCIATION

Eric Mensforth, C.B.E., M.A., M.I.Mech.E. (*Fellow*) was elected President of The Helicopter Association.

ROYAL SOCIETY OF ARTS

The Gold Albert Medal of The Royal Society of Arts for 1952 was awarded to Air Commodore Sir Frank Whittle, K.B.E., C.B., M.A., F.R.S. (*Fellow*).

FIRST CHURCHILL GOLD MEDAL—SOCIETY OF ENGINEERS

The First Churchill Gold Medal of The Society of Engineers was awarded to Air Commodore Sir Frank Whittle (*Fellow*). The Medal is awarded every two years for some notable achievement in the engineering world.

MEDALS AND AWARDS OF THE SOCIETY

Full particulars of the Medals and Awards of the Society were published in the July 1952 issue of the JOURNAL. These Medals and Awards were presented at the Fortieth Wilbur Wright Memorial Lecture on 29th May 1952.

JOURNAL PREMIUM AWARDS

JOURNAL Premium Awards, each of 15 guineas, were awarded to 12 authors whose papers were published in the JOURNAL for 1951. A complete list of authors and titles was published in the May 1952 JOURNAL.

## Royal Aeronautical Society Charter Scholarship 1952-53

The Charter Scholarship (value £300) was awarded to Mr. T. E. B. Bateman, who is studying Engineering at Pembroke College, Cambridge.

## The Geoffrey de Havilland Memorial Scholarship 1952-53

The Geoffrey de Havilland Memorial Scholarship (value £120) was awarded to Mr. J. A. H. Bailie, who is taking a Diploma Course at the College of Aeronautics, Cranfield.

## The Society of British Aircraft Constructors—Educational Grants

The Joint Selection Committee of The Society of British Aircraft Constructors and The Royal Aeronautical Society awarded Educational Grants to the following successful candidates on 30th July 1952:—

| | |
|---|---|
| D. C. Cook | D. L. Pegrum |
| M. Harding | J. Raine |
| H. T. Clifford-Hawthorne | R. G. M Scarfe |
| H. Bartham-Lake | P. Smith |
| J. D. Lean | |

These Grants are for the assistance of young men who are unable, for financial reasons, to obtain training in aeronautical engineering. All those awarded Society of British Aircraft Constructors' Grants are expected to qualify for a technical grade in The Royal Aeronautical Society.

## Finance

The Income and Expenditure Accounts and Balance Sheets of The Royal Aeronautical Society and Aeronautical Trusts Ltd. for 1952 are published with this report.

## Garden Party

In 1952 the Annual Garden Party was held at White Waltham Aerodrome, near Maidenhead, on 15th June, a month later than in previous years, with the hope that the weather would be more favourable. This hope was not, in fact, realised. However, the weather improved as the afternoon went on, and those present appeared to enjoy the comparative quiet of light aircraft and sailplanes.

(A full Report was published in the August 1952 JOURNAL.)

## Busk Studentship 1952-53

The Busk Studentship (value £165) was awarded to Mr. B. D. Henshall who is taking a Ph.D. Degree Course at the University of Bristol.

## Library

The Library continues to expand, but lack of space effectively brakes a large expansion programme. It is becoming more and more used as a source of information for Lectures, and other purposes, and many lantern slides are loaned for illustrations.

The number of books acquired during the year was 245 and about one thousand loans were made.

## Publications

During 1952 plans were made for a change in size and lay-out of the JOURNAL to take effect from the beginning of 1953.

The AERONAUTICAL QUARTERLY is now published at approximately six monthly intervals as an experiment. The circulation to non-members of the Society has increased slightly over the year.

The series of Monographs, sponsored by the Society and published by Chapman & Hall, is proving its worth. The first one, "The Properties of Metallic Materials at Low Temperatures" by Major Teed, is now in its second edition, and the other two, "The Structure and Mechanical Properties of Metals" by Bruce Chalmers (this will be reprinted in 1953), and "Adhesives for Wood" by R. A. G. Knight, are selling steadily.

Data Sheets have been brought up-to-date, and re-issued in further editions. There is no doubting the success of the Data Sheets, for the opinion that they are fulfilling their function is universal.

## Donations

During the year the Society received donations from:

Blackburn & General Aircraft Co. Ltd.
Bristol Aeroplane Co. Ltd.
De Havilland Aircraft Co. Ltd.
Dowty Equipment Ltd.
Folland Aircraft Ltd.
Sir George Nelson, Chairman, English Electric Co. Ltd.
Sir Frederick Handley Page.
Rolls-Royce Ltd.
Society of British Aircraft Constructors
Vickers-Armstrongs Ltd.

These the Council wish to acknowledge with gratitude and thanks. They also wish to acknowledge contributions from the Ministry of Supply and the Society of British Aircraft Constructors for the work of the Technical Committees of the Society.

## General

During the year the Society's Library and Committee Rooms have been used regularly by The Aeronautical Research Council, British Standards Institution, Society of British Aircraft Constructors, The Helicopter Association, and many others engaged in aeronautical work.

## Officers and Committees

The Council have expressed already their appreciation of the work of the late Mr. J. E. Hodgson, who so ably and for so many years acted as Honorary Librarian to the Society. An appreciation of his work for the Society was published in the May 1952 JOURNAL.

During the year Mr. C. F. Uwins has continued to act as Honorary Treasurer, and the Council take this opportunity of recording their appreciation of the results of his Treasurership.

To serve on any Committee of the Council means a sacrifice of leisure, and the Council acknowledges the service of the individual Member of Committee in devoting much time and energy towards the fulfilment of the Society's functions.

## Acknowledgments

The Society has received a number of books, pictures and other historical items, and the Council would like to place on record their grateful thanks to the donors for these gifts.

## Staff

The Staff of the Society has increased, especially in the technical department which is very nearly on a par with what it has been in previous years.

## Obituaries

The Council regret to record the death of the following Members of the Society:—

H. J. Andrews (*Fellow*)
A. Bailey (*Associate*)
W. H. Ballantyne (*Founder Member*)
Pilot Officer J. A. Caister (*Graduate*)
J. A. Choate (*Associate*)
Pilot Officer A. E. Creswell (*Student*)
J. P. Crossley (*Graduate*)
A. M. Desoutter (*Associate Fellow*)
W. C. Devereux (*Fellow*)
B. A. Duncan (*Fellow*)
Austin Eastwood (*Companion*)
G. G. W. Ebbutt (*Associate Fellow*)
T. W. Fazakerley (*Associate*)
Major O. T. Gnosspelius (*Fellow*)
Professor F. T. Hill (*Fellow*)
C. L. Hinings (*Associate Fellow*)
J. E. Hodgson (*Honorary Fellow*)
W. C. Jackson (*Associate Fellow*)
F. C. R. Jacques (*Associate*)
Wing Cmdr. B. J. Lynch (*Associate Fellow*)
J. Mackean (*Graduate*)
S. V. Maddox (*Associate*)
Professor N. A. V. Piercy (*Fellow*)
G. R. Raisbek (*Associate Fellow*)
J. K. Redman (*Associate Fellow*)
A. M. Richards (*Graduate*)
H. J. Ridgewell (*Associate*)
A. W. Robertson (*Student*)
Flt. Lieut. P. F. C. Swash (*Student*)
A. M. Taylor (*Associate Fellow*)
B. R. Townsend (*Graduate*)
Major C. C. Turner (*Fellow*)

# THE ROYAL

(INCORPORATED

## BALANCE SHEET

| 1951 Figures | | | | £ s. d. | £ s. d. |
|---|---|---|---|---|---|
| 5273 1 3 | *Current Liabilities*— Sundry Creditors ... ... ... ... ... ... ... | | | 4492 13 9 | |
| 2863 12 11 | Subscriptions and other amounts received in advance ... | | | 4434 11 2 | 8927 4 11 |
| 8136 14 2 | | | | | |
| | *Surplus*—(Subject to depreciation of Investments) | | | | |
| | *Publications Development Account*— | | | | |
| 2680 3 10 | Balance as at 31st December 1951 ... ... ... ... | | | 2680 3 10 | |
| — — — | *Reserve for Anglo-American Conference 1953* ... ... | | | 2000 0 0 | |
| | *Income and Expenditure Account*— | | | | |
| | Balance at 31st December 1951 ... ... | 4617 19 3 | | | |
| 4617 19 3 | *Add* Surplus of Income over Expenditure for year to date ... ... ... ... | 2196 11 6 | | 6814 10 9 | 11494 14 7 |
| 7298 3 1 | | | | | |
| £15434 17 3 | | | | | £20421 19 6 |

G. H. DOWTY, *President.*

C. F. UWINS, *Honorary Treasurer.*

### REPORT OF THE AUDITORS TO THE MEMBERS

In our opinion and to the best of our information and according to the explanations Society together with the accounts of the Royal Aeronautical Society Endowment Fund of the state of the Society's affairs as at 31st December 1952 and of its surplus for the

We have obtained all the information and explanations which to the best of our proper books of account and the above mentioned accounts are in agreement therewith.

3 Frederick's Place, Old Jewry, London, E.C.2.
12th March 1953.

## INCOME AND EXPENDITURE ACCOUNT

| 1951 Figures | | | | £ s. d. | £ s. d. |
|---|---|---|---|---|---|
| £ s. d. | To Establishment Charges— | | | | |
| 2059 2 8 | Ground Rent, Heating, Lighting, Insurance and Repairs | | | | 1631 16 7 |
| ,, | Office and Staff Expenses— | | | | |
| 8323 13 4 | Salaries ... ... ... ... ... ... ... | | | 8741 17 4 | |
| 620 0 5 | Staff Pension Premiums and Pension Paid ... ... | | | 1401 4 7 | |
| 1593 6 0 | Printing and Stationery ... ... ... ... ... | | | 1564 17 10 | |
| 1374 6 5 | Postages and Telephones ... ... ... ... ... | | | 1304 7 2 | |
| 41 12 3 | Office Equipment ... ... ... ... ... ... | | | 168 15 4 | |
| 783 10 3 | Other Charges ... ... ... ... ... ... | | | 725 3 9 | 13906 6 0 |
| 12736 8 8 | | | | | |
| 6239 18 6 | ,, Journal and Sundry Publications ... ... ... ... | | | | 5635 17 0 |
| ,, | Expenditure on Data Sheets— | | | | |
| 128 19 2 | *Less* amounts recoverable ... ... ... ... ... | | | | — — — |
| 596 6 2 | ,, Meetings ... ... ... ... ... ... ... | | | | 423 0 9 |
| 4741 4 0 | ,, Reserve for Anglo-American Aeronautical Conference 1953 | | | | 2000 0 0 |
| 517 0 3 | ,, Garden Party ... ... ... ... ... ... ... | | | | 476 13 6 |
| 442 0 7 | ,, Dinners and Receptions ... ... ... ... ... | | | | 495 3 8 |
| 1223 9 2 | ,, Library Expenses ... ... ... ... ... ... | | | | 1653 15 10 |
| 414 0 0 | ,, Branch Expenses ... ... ... ... ... ... | | | | 455 0 0 |
| 127 2 0 | ,, Prizes and Donations ... ... ... ... ... ... | | | | 257 15 6 |
| — — — | ,, Donation to Pritchard Testimonial Fund ... ... ... | | | | 1000 0 0 |
| 250 0 0 | ,, Charter Scholarship ... ... ... ... ... ... | | | | 216 13 4 |
| 293 12 8 | ,, Legal and Professional Charges ... ... ... ... | | | | 217 4 10 |
| — — — | ,, Balance, being surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... | | | | 2196 11 6 |
| £29769 3 10 | | | | | £30565 18 6 |

# AERONAUTICAL SOCIETY

BY ROYAL CHARTER 1949)

## 31st DECEMBER 1952

| 1951 Figures | | | | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|---|---|---|
| | | | *Current Assets—* | | | | | | |
| 1 | 0 | 0 | Stock of Journals and other publications ... ... ... | 1 | 0 | 0 | | | |
| 4927 | 9 | 8 | Sundry Debtors ... ... ... ... ... ... ... | 6640 | 2 | 11 | | | |
| 129 | 9 | 10 | Payments in Advance ... ... ... ... ... ... | 544 | 9 | 11 | | | |
| 576 | 8 | 2 | Cash at Bank and in Hand ... ... ... ... ... | 4070 | 7 | 9 | 11256 | 0 | 7 |
| 5634 | 7 | 8 | | | | | | | |
| 7801 | 4 | 2 | *Investments at Cost* ... ... ... ... ... ... | | | | 7801 | 4 | 2 |
| | | | Market value 31st December 1952: £6,979 (1951: £7,022) | | | | | | |
| | | | *Aeronautical Trusts Limited—* | | | | | | |
| 1 | 1 | 0 | 21 shares of 1/- each fully paid at cost ... ... ... | 1 | 1 | 0 | | | |
| 1948 | 4 | 5 | Amount due on current account ... ... ... ... | 1313 | 13 | 9 | 1314 | 14 | 9 |
| 1949 | 5 | 5 | | | | | | | |
| | | | *Printed Books, Binding, Old Prints, etc.—* | | | | | | |
| 50 | 0 | 0 | At nominal amount ... ... ... ... ... ... | | | | 50 | 0 | 0 |
| £15434 | 17 | 3 | | | | | £20421 | 19 | 6 |

OF THE ROYAL AERONAUTICAL SOCIETY

given to us, the above balance sheet and the annexed income and expenditure account of the
included in the annexed accounts of Aeronautical Trusts Limited give a true and fair view
year ended on that date.
knowledge and belief were necessary for our audit. In our opinion the Society has kept

(*Signed*) PRICE WATERHOUSE & CO.

## FOR THE YEAR ENDED 31st DECEMBER 1952

| 1951 Figures | | | | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|---|---|---|
| 22272 | 19 | 6 | By Annual Subscriptions ... ... ... ... ... ... | | | | 22541 | 6 | 0 |
| 2074 | 10 | 0 | „ Donations ... ... ... ... ... ... ... | | | | 2626 | 17 | 8 |
| 121 | 13 | 10 | „ Interest on Investments (*Less* Tax) ... ... ... ... | 118 | 17 | 4 | | | |
| 101 | 17 | 4 | „ Income Tax Recovered ... ... ... ... ... | 106 | 15 | 9 | | | |
| 4810 | 9 | 5 | „ Surplus on Endowment Fund Income and Expenditure Account for year ... ... ... ... ... ... | 4996 | 0 | 1 | 5221 | 13 | 2 |
| 5034 | 0 | 7 | | | | | | | |
| 4 | 11 | 3 | „ Examinations ... ... ... ... ... ... ... | | | | 176 | 1 | 8 |
| 383 | 2 | 6 | (Deficit) | | | | | | |
| £29769 | 3 | 10 | | | | | £30565 | 18 | 6 |

# AERONAUTICAL

## BALANCE SHEET

| 1951 Figures £ s. d. | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|
| | SHARE CAPITAL— | | | |
| | *Authorised*—40 shares of 1s. each ... ... ... ... | | 2 0 0 | |
| 1 1 0 | *Issued*—21 shares of 1s. each fully paid ... ... ... | | | 1 1 0 |
| | ROYAL AERONAUTICAL SOCIETY ENDOWMENT FUND— | | | |
| | *Capital Account*—(Subject to depreciation of Investments) | | | |
| 131649 12 1 | Balance at 31st December 1951... ... ... ... | | 132152 11 1 | |
| 5 5 0 | *Add*—Donations received during year ... ... ... | | 7 7 0 | |
| 497 14 0 | Entrance Fees received during year ... ... | | 614 13 0 | |
| 132152 11 1 | | | 132774 11 1 | |
| | *Income Account*— | | | |
| 9103 14 6 | Balance as at 31st December 1951 ... ... ... | | 9103 14 6 | 141878 5 7 |
| 141256 5 7 | | | | |
| | PILCHER MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 99 14 0 | As at 31st December 1951 ... ... | | 99 14 0 | |
| | *Income Account*— | | | |
| 74 9 4 | Balance at 31st December 1951 ... | 79 16 8 | | |
| 5 7 4 | *Add*—Income for year to date ... | 5 7 4 | 85 4 0 | 184 18 0 |
| 179 10 8 | | | | |
| | USBORNE MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 109 2 5 | As at 31st December 1951 ... ... | | 109 2 5 | |
| | *Income Account*— | | | |
| 82 7 0 | Balance at 31st December 1951 ... | 88 6 4 | | |
| 5 19 4 | *Add*—Income for year to date ... | 5 19 4 | 94 5 8 | 203 8 1 |
| 197 8 9 | | | | |
| | HERBERT AKROYD STUART FUND— | | | |
| | *Capital Account*— | | | |
| 691 9 0 | As at 31st December 1951 ... ... | | 691 9 0 | |
| | *Income Account*— | | | |
| 581 12 3 | Balance at 31st December 1951 ... | 598 4 1 | | |
| 16 11 10 | *Add*—Surplus of Income over Expenditure for year to date ... ... | 16 11 10 | 614 15 11 | 1306 4 1 |
| 1289 13 1 | | | | |
| | R.38 MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 981 13 10 | As at 31st December 1951 ... ... | | 981 13 10 | |
| | *Income Account*— | | | |
| 928 1 2 | Balance at 31st December 1951 ... | 987 0 4 | | |
| 58 19 2 | *Add*—Income for year to date ... | 58 19 2 | 1045 19 6 | 2027 13 4 |
| 1968 14 2 | | | | |
| 144892 13 3 | *Forward* | | | 145601 10 1 |

# TRUSTS LIMITED

## 31st DECEMBER 1952

| 1951 Figures | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | £ | s. | d. | £ | s. | d. | £ | s. | d. |
| 1 | 1 | 0 | CASH IN HAND ... ... ... ... ... ... ... | | | | | | | 1 | 1 | 0 |
| | | | ROYAL AERONAUTICAL SOCIETY ENDOWMENT FUND— | | | | | | | | | |
| | | | Leasehold Property at cost *less* amounts written off | | | | | | | | | |
| | | | 4, 8, and 9, Hamilton Place | | | | | | | | | |
| 14185 | 1 | 9 | At cost ... ... ... ... ... | 14185 | 1 | 9 | | | | | | |
| 6471 | 1 | 9 | *Less*—Amortisation written off to date | 7126 | 1 | 9 | 7059 | 0 | 0 | | | |
| 7714 | 0 | 0 | | | | | | | | | | |
| | | | Furniture at cost *less* depreciation | | | | | | | | | |
| 4570 | 5 | 0 | At cost ... ... ... ... ... | 4794 | 13 | 0 | | | | | | |
| 2716 | 5 | 0 | *Less*—Depreciation written off to date | 2955 | 13 | 0 | 1839 | 0 | 0 | | | |
| 1854 | 0 | 0 | | | | | | | | | | |
| 132065 | 11 | 3 | Investments at cost ... ... ... ... | | | | 132065 | 11 | 3 | | | |
| | | | Market value 31st December 1952, £109,027 (1951, £110,567), including £1,000 2½% Defence Bonds (unquoted) at cost | | | | | | | | | |
| 141633 | 11 | 3 | | | | | 140963 | 11 | 3 | | | |
| | | | Current Assets— | | | | | | | | | |
| 773 | 5 | 0 | Sundry Debtors ... ... ... | 750 | 0 | 0 | | | | | | |
| 797 | 13 | 9 | Cash at Bank ... ... ... ... | 1478 | 8 | 1 | 2228 | 8 | 1 | | | |
| 143204 | 10 | 0 | | | | | 143191 | 19 | 4 | | | |
| 1948 | 4 | 5 | *Less*—Amount due to the Royal Aeronautical Society ... ... ... ... | | | | 1313 | 13 | 9 | 141878 | 5 | 7 |
| 141256 | 5 | 7 | | | | | | | | | | |
| | | | PILCHER MEMORIAL FUND— | | | | | | | | | |
| 156 | 5 | 0 | Investment at cost ... ... ... ... ... ... | | | | 156 | 5 | 0 | | | |
| | | | Market value 31st December 1952: £120 (1951: £125) | | | | | | | | | |
| 23 | 5 | 8 | Cash at Bank ... ... ... ... ... ... ... | | | | 28 | 13 | 0 | 184 | 18 | 0 |
| 179 | 10 | 8 | | | | | | | | | | |
| | | | USBORNE MEMORIAL FUND— | | | | | | | | | |
| 174 | 11 | 1 | Investment at cost ... ... ... ... ... ... | | | | 174 | 11 | 1 | | | |
| | | | Market value 31st December 1952: £133 (1951: £139) | | | | | | | | | |
| 22 | 17 | 8 | Cash at Bank ... ... ... ... ... ... ... | | | | 28 | 17 | 0 | 203 | 8 | 1 |
| 197 | 8 | 9 | | | | | | | | | | |
| | | | HERBERT AKROYD STUART FUND— | | | | | | | | | |
| 1102 | 15 | 8 | Investment at cost ... ... ... ... ... ... | | | | 1102 | 15 | 8 | | | |
| | | | Market value 31st December 1952: £838 (1951: £870) | | | | | | | | | |
| 186 | 17 | 5 | Cash at Bank ... ... ... ... ... ... ... | | | | 203 | 9 | 3 | 1306 | 4 | 11 |
| 1289 | 13 | 1 | | | | | | | | | | |
| | | | R.38 MEMORIAL FUND— | | | | | | | | | |
| 1754 | 6 | 2 | Investment at cost ... ... ... ... ... ... | | | | 1754 | 6 | 2 | | | |
| | | | Market value 31st December 1952: £1,314 (1951: £1,365) | | | | | | | | | |
| 214 | 8 | 0 | Cash at Bank ... ... ... ... ... ... ... | | | | 273 | 7 | 2 | 2027 | 13 | 4 |
| 1968 | 14 | 2 | | | | | | | | | | |
| 144892 | 13 | 3 | *Forward* | | | | | | | 145601 | 10 | 11 |

## AERONAUTICAL

## BALANCE SHEET

| 1951 Figures £ s. d. | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|
| 144892 13 3 | *Forward* | | | 145601 10 11 |
| | EDWARD BUSK MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 449 6 1 | As at 31st December 1951 ... ... | | 449 6 1 | |
| | *Income Account*— | | | |
| 226 7 7 | Balance at 31st December 1951 ... | 233 13 9 | | |
| | *Add*—Surplus of Income over Expenditure for year to date ... ... | 5 11 6 | 239 5 3 | 688 11 4 |
| 682 19 10 | | | | |
| | EDWARD BUSK STUDENTSHIP IN AERONAUTICS— | | | |
| | *Capital Account*— | | | |
| 5418 12 7 | Balance at 31st December 1951 ... ... ... | | 5418 12 7 | |
| | *Add*—Profit on Realisation of Investment ... ... | | 1 0 0 | |
| | | | 5419 12 7 | |
| | *Less*—Further expenses on transfer from previous Trustees ... ... ... ... ... ... | | 2 7 3 | |
| | | | 5417 5 4 | |
| | *Income Account*— | | | |
| — — — | Surplus of Income over Expenditure for year to date | | 103 1 6 | 5520 6 10 |
| 5418 12 7 | | | | |
| | WILBUR WRIGHT MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 2136 17 11 | As at 31st December 1951 ... ... | | 2136 17 11 | |
| | *Income Account*— | | | |
| 219 10 10 | Balance at 31st December 1951 ... | 225 9 2 | | |
| | *Add*—Surplus of Income over Expenditure for year to date ... ... | 5 18 4 | 231 7 6 | 2368 5 5 |
| 2362 7 1 | | | | |
| | SIMMS GOLD MEDAL FUND— | | | |
| | *Capital Account*— | | | |
| 527 15 9 | As at 31st December 1951 ... ... | | 527 15 9 | |
| | *Income Account*— | | | |
| 65 5 11 | Balance at 31st December 1951 ... | 73 9 9 | | |
| | *Add*—Surplus of Income over Expenditure for year to date ... ... | 9 1 6 | 82 11 3 | 610 7 0 |
| 601 5 6 | | | | |
| | ALSTON MEMORIAL FUND— | | | |
| | *Capital Account*— | | | |
| 245 6 0 | As at 31st December 1951 ... ... | | 245 6 0 | |
| | *Income Account*— | | | |
| 73 10 9 | Balance at 31st December 1951 ... | 77 8 11 | | |
| | *Add*—Surplus of Income over Expenditure for year to date ... ... | 3 18 2 | 81 7 1 | 326 13 1 |
| 322 14 11 | | | | |
| 154280 13 2 | *Forward* | | | 155115 14 7 |

## TRUSTS LIMITED—*Continued*

### 31st DECEMBER 1952

| 1951 Figures £ s. d. | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|
| 144892 13 3 | *Forward* | | | 145601 10 11 |
| | EDWARD BUSK MEMORIAL FUND— | | | |
| 658 8 8 | Investments at cost ... ... ... ... ... ... | | 658 8 8 | |
| | Market value 31st December 1952: £575 (1951: £591) | | | |
| 24 11 2 | Cash at Bank ... ... ... ... ... ... ... | | 30 2 8 | 688 11 4 |
| 682 19 10 | | | | |
| | EDWARD BUSK STUDENTSHIP IN AERONAUTICS— | | | |
| 4906 10 0 | Investments at valuation 31st December 1951 ... ... | | 4806 10 0 | |
| | Market value 31st December 1952: £4,675 (1951: £4,906) | | | |
| 573 17 7 | Cash at Bank ... ... ... ... ... ... ... | | 713 16 10 | 5520 6 10 |
| 5480 7 7 | | | | |
| 61 15 0 | (*less* Sundry Creditors) | | | |
| 5418 12 7 | | | | |
| | WILBUR WRIGHT MEMORIAL FUND— | | | |
| 2250 14 9 | Investments at cost ... ... ... ... ... ... | | 2250 14 9 | |
| | Market value 31st December 1952: £2,029 (1951: £2,070) | | | |
| 111 12 4 | Cash at Bank ... ... ... ... ... ... ... | | 117 10 8 | 2368 5 5 |
| 2362 7 1 | | | | |
| | SIMMS GOLD MEDAL FUND— | | | |
| 504 12 0 | Investments at cost ... ... ... ... ... ... | | 504 12 0 | |
| | Market value 31st December 1952: £403 (1951: £414) | | | |
| 96 13 6 | Cash at Bank ... ... ... ... ... ... ... | | 105 15 0 | 610 7 0 |
| 601 5 6 | | | | |
| | ALSTON MEMORIAL FUND— | | | |
| 290 0 0 | Investments at cost ... ... ... ... ... ... | | 290 0 0 | |
| | Market value 31st December 1952: £283 (1951: £285) | | | |
| 32 14 11 | Cash at Bank ... ... ... ... ... ... ... | | 36 13 1 | 326 13 1 |
| 322 14 11 | | | | |
| 154280 13 2 | *Forward* | | | 155115 14 7 |

# AERONAUTICAL

## BALANCE SHEET

| 1951 Figures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | £ | s. | d. | £ | s. d. |
| 154280 | 13 | 2 | *Forward* | | | | 155115 | 14 7 |
| | | | GEOFFREY DE HAVILLAND MEMORIAL FUND— | | | | | |
| | | | *Capital Account*— | | | | | |
| 4175 | 17 | 5 | As at 31st December 1951 ... ... | | | | 4175 17 5 | |
| | | | *Income Account*— | | | | | |
| 242 | 1 | 0 | Balance at 31st December 1951 ... | 325 | 4 | 8 | | |
| 83 | 3 | 8 | *Add*—Surplus of Income over Expenditure for year to date ... ... | 1 | 6 | 2 | 326 10 10 | 4502 8 3 |
| 4501 | 2 | 1 | | | | | | |
| £158781 | 15 | 3 | | | | | | £159618 2 10 |

REPORT OF THE AUDITORS TO THE

In our opinion and to the best of our information and according to the explanations a true and fair view of the state of the Company's affairs and of the Funds administered by it

We have obtained all the information and explanations which to the best of our proper books of account and the above mentioned accounts, which are in agreement therewith.

3 Frederick's Place, Old Jewry, London, E.C.2.
12th March 1953.

# AERONAUTICAL

## INCOME AND EXPENDITURE ACCOUNTS

### ROYAL AERONAUTICAL SOCIETY

| 1951 Figures | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | | | | £ | s. d. |
| 655 | 0 | 0 | To Amortisation of Leasehold Property ... ... ... ... ... ... | | | | 655 | 0 0 |
| 228 | 10 | 0 | ,, Depreciation of Furniture ... ... ... ... ... ... ... | | | | 239 | 8 0 |
| 10 | 10 | 0 | ,, Legal Expenses ... ... ... ... ... ... ... ... | | | | 5 | 5 0 |
| 4810 | 9 | 5 | ,, Surplus of Income over Expenditure for year transferred to Royal Aeronautical Society ... ... ... ... ... ... ... | | | | 4996 | 0 1 |
| £5704 | 9 | 5 | | | | | £5895 | 13 1 |

### PILCHER

| £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|
| 5 | 7 | 4 | To Income for year carried to Balance Sheet ... ... ... ... ... | 5 | 7 | 4 |
| £5 | 7 | 4 | | £5 | 7 | 4 |

### USBORNE

| £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|
| 5 | 19 | 4 | To Income for year carried to Balance Sheet ... ... ... ... ... | 5 | 19 | 4 |
| £5 | 19 | 4 | | £5 | 19 | 4 |

### HERBERT AKROYD

| £ | s. | d. | | £ | s. | d. |
|---|---|---|---|---|---|---|
| 21 | 0 | 0 | To 1952 Award ... ... ... ... ... ... ... ... ... | 21 | 0 | 0 |
| 16 | 11 | 10 | ,, Surplus of Income over Expenditure for year carried to Balance Sheet ... | 16 | 11 | 10 |
| £37 | 11 | 10 | | £37 | 11 | 10 |

## TRUSTS LIMITED—*Continued*

### 31st DECEMBER 1952

| 1951 Figures | | | | £ | s. d. | £ | s. d. | £ | s. d. |
|---|---|---|---|---|---|---|---|---|---|
| £ | s. d. | | | | | | | | |
| 154280 | 13 | 2 | *Forward* | | | | | 155115 | 14 7 |
| | | | GEOFFREY DE HAVILLAND MEMORIAL FUND— | | | | | | |
| 4175 | 17 | 5 | Investment at cost ... ... ... ... ... ... | | | 4175 | 17 5 | | |
| | | | Market value 31st December 1952: £3,397 (1951: £3,407) | | | | | | |
| 325 | 4 | 8 | Cash at Bank ... ... ... ... ... ... ... | | | 326 | 10 10 | 4502 | 8 3 |
| 4501 | 2 | 1 | | | | | | | |
| £158781 | 15 | 3 | | | | | | £159618 | 2 10 |

MEMBERS OF AERONAUTICAL TRUSTS LTD.

given to us the above balance sheet and the annexed income and expenditure account give as at 31st December 1952 and of the surplus of the Funds for the year ended on that date. knowledge and belief were necessary for our audit. In our opinion the company has kept give in the prescribed manner the information required by the Companies Act, 1948.

(*Signed*) PRICE WATERHOUSE & CO.

## TRUSTS LIMITED

## FOR THE YEAR ENDED 31st DECEMBER 1952

### ENDOWMENT FUND

| 1951 Figures | | | | £ | s. d. |
|---|---|---|---|---|---|
| £ | s. d. | | | | |
| 2642 | 1 | 4 | By Interest on Investments (Gross) ... ... ... ... ... ... | 2642 | 1 4 |
| 815 | 11 | 8 | ,, Interest on Investments (*less* tax) ... ... ... ... ... ... | 969 | 7 3 |
| 736 | 6 | 9 | ,, Refund of Income Tax ... ... ... ... ... ... ... | 784 | 4 6 |
| 1500 | 0 | 0 | ,, Rents Receivable ... ... ... ... ... ... ... ... | 1500 | 0 0 |
| 10 | 9 | 8 | (Interest on deposit account) | | |
| £5704 | 9 | 5 | | £5895 | 13 1 |

### MEMORIAL FUND

| £ | s. d. | | £ | s. d. |
|---|---|---|---|---|
| 5 | 7 4 | By Interest on Investments (Gross) ... ... ... ... ... ... | 5 | 7 4 |
| £5 | 7 4 | | £5 | 7 4 |

### MEMORIAL FUND

| £ | s. d. | | £ | s. d. |
|---|---|---|---|---|
| 5 | 19 4 | By Interest on Investments (Gross) ... ... ... ... ... ... | 5 | 19 4 |
| £5 | 19 4 | | £5 | 19 4 |

### STUART FUND

| £ | s. d. | | £ | s. d. |
|---|---|---|---|---|
| 37 | 11 10 | By Interest on Investments (Gross) ... ... ... ... ... ... | 37 | 11 10 |
| £37 | 11 10 | | £37 | 11 10 |

# AERONAUTICAL

## INCOME AND EXPENDITURE ACCOUNTS

R.38

| 1951 Figures | | | | | |
|---|---|---|---|---|---|
| £ | s. | d. | | £ | s. d. |
| 58 | 19 | 2 | To Income for year carried to Balance Sheet ... ... ... ... ... | 58 | 19 2 |
| £58 | 19 | 2 | | £58 | 19 2 |

### EDWARD BUSK

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| 21 | 0 | 0 | To 1952 Award ... ... ... ... ... ... ... ... ... | 21 | 0 0 |
| 7 | 6 | 2 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 5 | 11 6 |
| £28 | 6 | 2 | | £26 | 11 6 |

### EDWARD BUSK STUDENTSHIP

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| | | | To 1952 Award ... ... ... ... ... ... ... ... ... | 55 | 0 0 |
| | | | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 103 | 1 6 |
| | | | | £158 | 1 6 |

### WILBUR WRIGHT

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| 75 | 0 | 0 | To 1952 Award ... ... ... ... ... ... ... ... ... | 75 | 0 0 |
| 5 | 18 | 4 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 5 | 18 4 |
| £80 | 18 | 4 | | £80 | 18 4 |

### SIMMS GOLD

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| 8 | 3 | 6 | To 1952 Award ... ... ... ... ... ... ... ... ... | 7 | 5 10 |
| 8 | 3 | 10 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 9 | 1 6 |
| £16 | 7 | 4 | | £16 | 7 4 |

### ALSTON

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| 5 | 0 | 0 | To 1952 Award ... ... ... ... ... ... ... ... ... | 5 | 0 0 |
| 3 | 18 | 2 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 3 | 18 2 |
| £8 | 18 | 2 | | £8 | 18 2 |

### GEOFFREY de HAVILLAND

| £ | s. | d. | | £ | s. d. |
|---|---|---|---|---|---|
| 120 | 0 | 0 | To 1952 Award ... ... ... ... ... ... ... ... ... | 120 | 0 0 |
| 83 | 3 | 8 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... | 1 | 6 2 |
| £203 | 3 | 8 | | £121 | 6 2 |

## TRUSTS LIMITED—*Continued*

## FOR THE YEAR ENDED 31st DECEMBER 1952

### MEMORIAL FUND

| 1951 Figures | | | | |
|---|---|---|---|---|
| £ s. d. | | | £ s. d. | |
| 58 19 2 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 58 19 2 | |
| £58 19 2 | | | £58 19 2 | |

### MEMORIAL FUND

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| 15 17 0 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 20 3 8 | |
| 4 13 2 | ,, Interest on Investments (*less* tax) ... ... ... ... ... ... | | 2 5 6 | |
| 7 16 0 | ,, Refund of Income Tax ... ... ... ... ... ... ... | | 4 2 4 | |
| £28 6 2 | | | £26 11 6 | |

### IN AERONAUTICS

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| | By Interest on Investments (Gross) ... ... ... ... ... ... | | 126 11 9 | |
| | ,, Interest on Investments (*less* tax) ... ... ... ... ... ... | | 31 9 9 | |
| | | | £158 1 6 | |

### MEMORIAL FUND

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| 80 18 4 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 80 18 4 | |
| £80 18 4 | | | £80 18 4 | |

### MEDAL FUND

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| 16 7 4 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 16 7 4 | |
| £16 7 4 | | | £16 7 4 | |

### MEMORIAL FUND

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| 8 18 2 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 8 18 2 | |
| £8 18 2 | | | £8 18 2 | |

### MEMORIAL FUND

| £ s. d. | | | £ s. d. | |
|---|---|---|---|---|
| 121 6 2 | By Interest on Investments (Gross) ... ... ... ... ... ... | | 121 6 2 | |
| 81 17 6 (Refund of Income Tax) | | | | |
| £203 3 8 | | | £121 6 2 | |

# New Zealand Division

## FOURTH ANNUAL REPORT: FOR YEAR ENDED 31st DECEMBER 1952

DURING the year the activities of the Society in New Zealand have shown satisfactory progress. The most prominent events apart from the normal branch activities have been the Aviation Industries Dinner and the series of film evenings given to the general public. At the same time the membership of the Society has remained practically static. The technical membership still remains just below 100, which is probably due to insufficient appreciation of the value of professional status among those actively employed in the Aircraft Industry. The total branch membership has not yet exceeded 400. It is hoped that a special effort will be made during the coming year to exceed these figures.

The Rules for the operation of the New Zealand Division have been drawn up by Council and circulated to all members. They are now tabled for consideration and approval, after which they will be submitted to the Council of the Society for final confirmation.

The conditions for the award of the Henry Wigram Memorial Lecture were approved at the last Annual General Meeting and circulated to members. The establishment of this award, which is designed to provide the most important aeronautical address on New Zealand, received favourable press publicity in conjunction with the publication of a book on the life of Sir Henry Wigram. It is hoped that this award will stimulate lectures of high technical merit or economic worth which will advance the interests of aeronautics in New Zealand.

During the year two film evenings of outstanding interest were presented at all Branches. The Division is indebted to the Director of Civil Aviation and his staff for the assistance given, and particularly for the services of technical experts who gave introductory talks to the various films. These meetings were well supported by the public in all four centres, and have aroused considerable public interest in aviation activities. The problem of obtaining suitable films for exhibition has caused some concern. The main source is the large industrial and commercial organisations who themselves initiate or prepare films on aviation topics. In this matter the Division gratefully acknowledges the generosity of the Shell and Vacuum Oil Companies for their assistance. There is no doubt that these technical and semi-technical films are a medium particularly suited to the activities of the Division and its Branches.

The Aviation Industries Dinner, sponsored by the Society, was held on 7th July in Wellington. It was attended by the Prime Minister and members of Cabinet, as well as representatives from all sections of the Industry. The President of the N.Z. Division, who was in the Chair, took the opportunity of stressing the importance of aviation to the welfare of the country and its national economy.

It is pleasing to report that during the year an address entitled "Civil Aviation in the Second Elizabethan Era" given by the Vice-President, Mr. G. N. Roberts, was published in the Society's JOURNAL (November 1952).

### DIVISIONAL COUNCIL 1952

The Division Council for 1952 was elected by postal ballot from all members known to be resident in New Zealand:—

*President*

Sir Arthur Nevill, K.B.E., C.B., M.Sc., A.F.R.Ae.S.

*Vice-President*

G. N. Roberts, C.B.E., A.R.Ae.S.

*Honorary Secretary*

T. T. N. Coleridge, B.E., A.F.R.Ae.S.

*Honorary Assistant Secretary*

Squadron Leader J. D. Robins, D.F.C., A.R.Ae.S. (part year)

*Honorary Treasurer*

A. O. Kemp, A.R.A.N.Z., A.C.A.I. (also Honorary Assistant Secretary part year)

*Council Members*

H. F. T. Adams, M.A., A.F.R.Ae.S.
B. G. de Bray, M.Sc., A.F.R.Ae.S.
A. W. Dingle, A.F.R.Ae.S.
C. W. Labette, A.F.R.Ae.S.
E. A. Gibson, O.B.E., A.F.R.Ae.S.
C. G. Andrews, D.F.C., A.F.R.Ae.S.
F. F. J. Butler, M.B.E., A.F.R.Ae.S.
Air Commodore G. Carter, A.F.R.Ae.S.

Details of the activities of each Branch are as follows:—

### AUCKLAND BRANCH

*Chairman*: D. J. Patterson, M.B.E., A.R.Ae.S.

*Honorary Secretary*: A. Jardine, A.F.R.Ae.S.

*Honorary Treasurer*: G. W. E. Clancey.

*Committee*: G. B. Bolt, A.F.R.Ae.S., B. G. de Bray, M.Sc., A.F.R.Ae.S., J. H. Malcombe, F. Sorrell, A. Vause, A.R.Ae.S. and Squadron Leader R. Leonard, O.B.E., A.R.Ae.S.

A very successful Aviation Interests gathering was sponsored by the Branch with an attendance of over 150. Mr. G. N. Roberts' address on that occasion was

subsequently reproduced in part in the Society's JOURNAL. The Aviation film evening drew an attendance of approximately 270 people.

Apart from these, the average attendance at meetings was 32.

Although 23 new members have been enrolled, the total membership has fallen to 130 from the last year figure of 140; this is largely because of persons leaving the Branch area.

PALMERSTON NORTH BRANCH

*Chairman*: C. W. Labette, A.F.R.Ae.S.

*Vice-Chairman*: Squadron Leader G. S. Evatt, A.R.Ae.S.

*Honorary Secretary*: A. J. Smaill, A.R.Ae.S.

*Honorary Treasurer*: Miss S. T. Murphy.

*Committee*: J. S. Brown, A. W. Dingle, R. McDonald and R. H. Nokes.

During the year ten meetings were held, one in conjunction with the Institute of Engineers; another was the outstanding film evening open to the public, which was very largely attended.

Because of transfers of members over the year, in particular N.Z. National Airways Corporation staff to Harewood, the membership showed a decline from 91 in the previous year to 78, there being 11 new members apart from the transfers.

WELLINGTON BRANCH

*Chairman*: B. Cornthwaite, A.R.Ae.S.

*Honorary Secretary*: F. F. J. Butler, M.B.E., A.F.R.Ae.S.

*Honorary Treasurer*: L. Clarke.

*Committee*: A. M. Harvie, A.F.C., J. J. Busch, C. G. Andrews, D.F.C., A.F.R.Ae.S., Wing Commander Abernothy and Flight Lieut. R. B. Bolt, D.F.C., A.R.Ae.S.

During the year two public film evenings were given, the first with an attendance of about 150 with many having to be turned away, and the second in a larger hall with an attendance of over 200. Both these evenings were very successful. Six other meetings were held during the year with attendances ranging from 18 to 64.

A Branch prize was instituted during the year for the lecture or paper voted by the Committee to be the most interesting and informative. The award for 1952 was made to A. C. Elworthy for his paper on Aircraft Gas Turbines.

During the year 18 new members were enrolled, but because of transfers and resignations the Branch membership decreased from 129 to 120.

CHRISTCHURCH BRANCH

*Chairman*: H. F. T. Adams, M.A., A.F.R.Ae.S.

*Honorary Secretary*: A. H. T. Brazier, A.F.R.Ae.S.

Through losses in membership due to the transfer away from Christchurch of a large number of the original members, the activities of the Branch have been practically brought to a standstill.

Two meetings were held during the year, including a very successful film evening, the programme of which was supplied by the courtesy of the Director of Civil Aviation.

Membership of the Branch is now approximately 25 and it is hoped that with the transfer of National Airways Corporation Engineering Headquarters to Harewood, the activities of the Branch will be renewed on a normal scale during 1953.

## Membership of the Division

| | *As at Jan.* 1952 | *As at Jan.* 1953 |
|---|---|---|
| Fellows | — | — |
| Associate Fellows | 29 | 28 |
| Associates | 54 | 55 |
| Graduates | 5 | 7 |
| Students | 1 | 1 |
| Companions | 3 | 3 |
| | 92 | 94 |

Three Asociates and one Graduate included on the Division Roll are actually resident oversea.

## Financial Statement

A statement showing the financial position of the Division as at 31st December 1952 is published on p. 266.

## Lectures

A list of papers and lectures given throughout the Branches during the year is as follows (some of these have been given at more than one Branch):—

"Grass Surfaces on Aerodromes and Soil Erosion," by Mr. Maddern.

Reading and Discussion of the Paper on Delta Wing Aircraft given by the Chief Designer of A. V. Roe & Co. Ltd., by P. Clayton.

"Air Force Armament Methods," by Flight Lieut. Jolly.

Descriptive Talk on a Recent Trip to the United States, by C. W. Labette and A. Kimber.

"Air Transport in the Modern State," by E. A. Gibson.

"Modern Armaments," by Squadron Leader Tucker.

"Aerodromes and Aerodrome Control"—combined meeting with Institute of Engineers—by A. W. Dingle.

Talk on 1952 Farnborough Show and on Aerial Top-Dressing Aircraft Project, by Paul Haywood.

"Air Transport Trends and Developments," by Sir Leonard Isitt, K.B.E.

"Recent Development in Aircraft Armament," by Flight Lieut. S. G. Thompson, M.B.E.

"Recent Refinements in Sailplane Design," by C. A. Hookings.

"Recent Developments in High Altitude Gliding," by J. R. Court.

"Aircraft Accident Investigation and Prevention," by B. Cornthwaite.

"The International Air Transport Association—U.N.O. of the Air Travel World" by H. M. Denton.

"Aerial Mapping," by P. Van Asch.

"Considerations Required Prior to the Choice of Airline Aircraft," by C. W. Labette.

"Some Recent Developments in British and American Civil Aircraft," by G. B. Bolt.

"The History of Aviation Fields," by T. T. N. Coleridge.

"Meteorological Services to Aviation," by Dr. M. A. F. Barnett.

"Civil Aviation in the Modern State," by E. A. Gibson.

"Aircraft Gas Turbines," by A. C. Elworthy (awarded Wellington Branch Prize).

"Air Traffic Control in United Kingdom and Possible Application of the Methods to N.Z. Conditions," by G. S. Greagor and E. D. Gurney.

On many occasions films were shown either in conjunction with papers or as separate evenings. On some occasions general discussions also were held.

## Divisional Council for 1953

The following were elected by postal ballot for the Divisional Council for 1953:—

Sir Arthur Nevill, A.F.R.Ae.S. (Wellington), T. T. N. Coleridge, A.F.R.Ae.S. (Wellington), E. A. Gibson, A.F.R.Ae.S. (Wellington), C. G. Andrews, A.F.R.Ae.S. (Wellington), F. F. J. Butler, A.F.R.Ae.S. (Wellington), Air Commodore G. Carter, A.F.R.Ae.S. (Wellington), C. W. Labette, A.F.R.Ae.S. (Wellington), B. Cornthwaite, A.R.Ae.S. (Wellington), G. N. Roberts, A.R.Ae.S. (Auckland), H. F. T. Adams, A.F.R.Ae.S. (Christchurch), Squadron Leader G. S. Evatt, A.R.Ae.S. (Palmerston North), J. S. Brown, A.R.Ae.S. (Palmerston North).

## ROYAL AERONAUTICAL SOCIETY — NEW ZEALAND DIVISION
## STATEMENT OF RECEIPTS AND PAYMENTS FOR YEAR ENDED 31st DECEMBER 1952

*Receipts*

| | £ | s. | d. |
|---|---|---|---|
| Balances at 1/1/52:— | | | |
| National Bank of New Zealand ... | 302 | 0 | 8 |
| Petty Cash ... ... ... ... | 4 | 7 | 9 |
| Subscriptions, entrance fees, sale of badge | 189 | 14 | 6 |
| | £496 | 2 | 11 |

*Payments*

| | £ | s. | d. |
|---|---|---|---|
| Remittance to Royal Aeronautical Society, London, on account of 1951 subscriptions ... ... ... ... ... | 55 | 3 | 0 |
| Part reimbursement to Branches for Divisional Members 1952 Subscriptions:— | | | |
| Auckland ... ... ... ... | 3 | 0 | 0 |
| Wellington ... ... ... ... | 3 | 0 | 0 |
| Palmerston North ... ... ... | 1 | 10 | 0 |
| Christchurch ... ... ... ... | 1 | 0 | 0 |
| Grants to Branches for Film Evening Expenses:— | | | |
| Auckland ... ... ... ... | 5 | 10 | 0 |
| Christchurch ... ... ... ... | 5 | 10 | 0 |
| Postages, stamps, telegrams and Customs charges ... ... ... ... ... | 7 | 1 | 6 |
| Stationery ... ... ... ... ... | 34 | 17 | 11 |
| Advertising ... ... ... ... ... | 2 | 15 | 4 |
| Hire of Lecture Hall ... ... ... | 1 | 10 | 0 |
| Bank Fees ... ... ... ... ... | | 10 | 0 |
| Balances at 31/12/52:— | | | |
| National Bank of New Zealand ... | 371 | 12 | 10 |
| Petty Cash ... ... ... ... | 3 | 2 | 4 |
| | £496 | 2 | 11 |

I have audited the accounts of the Royal Aeronautical Society (N.Z. Division) and the above is a true and correct statement of receipts and payments for the year ended 31st December 1952.

(*Signed*) B. W. J. HOULT
B. Com. A.R.A.N.Z.
*Honorary Auditor*

# CORRESPONDENCE

## *The Scope and Limitations of the Photoelastic Method of Stress Analysis —A Correction*

*(The following correction to his paper, published in the March* 1953 JOURNAL *has been received from Colonel H. T. Jessop.)*

10*th March* 1953.

Sir,—In the course of my written replies to the discussion which followed my lecture on 27th November 1952, I quoted in reply to Mr. Hickson some results from a mathematical solution for the stresses in a sphere under diametral compression. The authors have since informed me that they have found an error which invalidates their solution, but unfortunately this was discovered too late for a correction to be made in the report published in the March number of the JOURNAL.

The three paragraphs containing reference to this solution (p. 138 right hand column), commencing "Another exact solution . . ." and ending ". . . to stress-concentration problems on a boundary," should therefore be deleted.

In their place I should like to add the following:—

"The results in such solutions, however, dealing with stress-concentrations on the boundaries of semi-infinite solids, will not necessarily be comparable with those in cases where the effect of the stress-concentration may tend to alter the distribution over the whole of the stressed body. What the effect in such problems will be it is impossible to predict. It may be that Mr. Hickson's tentative principles will eventually be shown to hold in such cases also, but until more evidence is available I prefer to treat the Poisson's ratio effect as an entirely unknown factor."

H. T. JESSOP.

## *Stressing of Circular Frames*

17*th March* 1953.

Sir,—With reference to the paper by K. J. Dallison, "Stressing of Circular Frames in a Non-Tapering Fuselage, p. 161 of the March 1953 JOURNAL, I note that he gives me credit for the invention of what he describes as "an alternative method of solution for moment and tangential loading." I should like to point out, as I did in my paper in the JOURNAL (November 1946), that the method was used in N.A.C.A. Technical Note 929, 1944. I may have elaborated it somewhat, but the original idea was not my own.

W. J. GOODEY.

17*th March* 1953.

Sir,—With reference to the very interesting paper by K. J. Dallison I would like, if I may, to discuss an aspect of the subject which Mr. Dallison does not appear to have dealt with and which could, in my opinion, be of importance.

It is not infrequently the case that aircraft fuselages are designed, in the interests of structural efficiency, so that the applied skin shear stresses have greater values in certain localities than the appropriate shear buckling stresses, and this state is allowed provided that permanent deformation and failure of the skin, among other things, do not occur under the prescribed conditions of the design case. Similarly, fuselage bending moments are applied under which that part of the skin in compression is accepted although not fully effective.

A result of this is that the shear modulus $G$ is not necessarily fully effective and will, in general, vary about the section perimeter depending on the magnitude of the local shear flow applied. If, under fuselage bending the skin in compression is not fully effective, the section principal axes will no longer coincide with the section axes of symmetry but will undergo a translation towards the tension fibres and a rotation depending on the direction of the axis about which the applied resultant bending moment acts. The effective shear moduli, the section principal axis location, the section bending modulus, etc., will have unique values for given values of applied bending moment, shear force and torque.

Stress configurations such as these occur at stations along the fuselage which are remote from points of load application, and consequently must be particularly significant in regions of shear distortion where load—transmitting frames are located. The skin in the region of such a frame might be reduced in effectiveness by the loads applied at the frame, or by the local frame loads in combination with the effects of loads already applied to the fuselage elsewhere and transmitted to the skin and its associated stringers in the region of the frame.

It follows that the frame and skin shear flow analysis can no longer be based on the assumption of symmetry about an axis in the plane of the frame or fuselage section: the number of unknown shear flow values ($x_p$) to be determined will be substantially increased as a result.

A more serious difficulty would, I think, be the assessment of the skin effective shear modulus and its variation around the fuselage section perimeter in the neighbourhood of a frame. It might be possible to introduce into Mr. Dallison's energy expressions additional terms to account direct for the modification to the shear modulus and for the ineffectiveness of the skin in compression. Alternatively, a procedure of "successive approximations" could perhaps be adopted whereby as a first step assumed values of $G$ are introduced to calculate an approximate shear distribution. The second step would be to re-estimate the shear modulus variation around the perimeter using, in association with the compression on the skin, the shear distribution already calculated; a second estimate of shear distribution based thereon being made, and so on.

I would be very interested to hear Mr. Dallison's views on the foregoing. Also, could he please say whether there is any experimental work to indicate the effects of buckled skin on the shear flow distribution around a frame?

B. SARAVANOS, *Associate Fellow.*

In reply to Mr. Saravanos:—

1. *Variation of the shear modulus.*

(*a*) *Overall* changes in the shear modulus would have only a small effect on the shear distribution at a flexible frame and none at all at a rigid frame. Thus a change of 100 per cent. in the value of the shear modulus would merely double or halve the value of $A/B$, with small change in the shear distribution.

(*b*) *Local* changes in the shear modulus would be significant in the neighbourhood of a loaded rigid frame, but less so near a flexible frame. Thus for values of $A/B<10$ (*i.e.* a comparatively rigid frame), the shear terms in the energy equation are paramount, and the shear flow is proportional to $G \sin \alpha$ (as is evident from Section 14, (*b*), p. 158). If $G$ varies round the frame, the shear distribution will be modified, and will in fact no longer be sinusoidal. The effect will diminish with increasing flexibility as the bending terms become progressively more important.

(*c*) The value of $G$ to be used at a particular angular station would be a mean value obtained by integrating the stress-strain curve between zero and an assumed maximum stress. This mean value would lie between $G$ and $G_s$ (secant modulus), in general being nearer to $G$ than to $G_s$. In estimating the maximum shear stress, a method of successive approximations could be used, as suggested by Mr. Saravanos, but in most cases a first estimate should suffice.

(*d*) Analytical terms based on post buckling behaviour of the skin could be included in the energy equation, but the deriving of such terms is outside the scope of the present investigation.

2. *Compression buckling of the skin.*

(*a*) In general, compression buckling, whether from local or remote loading, would occur over a narrow angular range of the skin. For transport and bomber aircraft, where the fuselage is designed mainly by bending in a vertical plane, regions of high compressive stress will in general be regions of low shear loading.

(*b*) The chief effect of compression buckling will thus be to increase the strain energy of skin and stringers in end load. It will be significant, therefore, only in those cases where the end load in skin and stringers is significant, *i.e.* when $A/B>100$ and $A \geqslant 10^4$. The normal engineering procedure of taking " 15 $t$ of skin on each side of the rivet " working with the stringer in compression seems therefore to look after this effect adequately, and even to over-allow for it.

(*d*) Where a more refined calculation is required, it will be necessary to calculate a mean value of the modulus on the lines of paragraph 1(*c*).

3. *Conclusion.*

Shear buckling might modify the skin shear distribution at a rigid frame, and to a less extent at a flexible frame. In general the effect should be small, except with severe buckling near a rigid frame.

Compression buckling will generally occur in regions of low shear loading. Its effect on the skin shear distribution will be small, and is probably already over-allowed for by using standard engineering estimates of " effective skin areas " in regions of compressive stress.

4. *Experimental results.*

The writer knows of no experimental results which show the effect of buckling on the skin shear distribution at a loaded frame. It would be interesting to compare any such results that become available with the predictions set out above.

K. J. DALLISON.

## *Temperature Control*

18*th March* 1953.

Sir,—Dr. Still's paper " Temperature Control of Jet-Engined Aircraft " in the February 1953 JOURNAL has included a chart (Fig. 19) which needs care in application. Its derivation is not given but it would appear to be that published by the American Society of Heating and Ventilating Engineers. If this is so the comfort zones marked were decided from subjective tests on American people and as such are not strictly applicable to non-Americans as the body is habituated to local climatic conditions. In support of this the A.S.H.V.E. found that the standards for people from different districts varied but for simplification the chart shown was published. In this writer's opinion the acceptable tolerance on the values shown could be large, at least on dry bulb temperature. The " Effective Temperature " should be suited to the route flown if economic factors and the equipment allow in commercial aircraft. In military aircraft of short flight duration the tolerance could be very large.

" Effective Temperature " is a subjective standard which is not a simple function of humidity, dry bulb temperature, etc., as it is complicated by factors such as the presence of radiant heating. The word " Temperature " is misleading as it implies objective measurement and by its use one tends to overlook the most important human factor. If one used, say, " Comfort Standard " this danger might be overcome, especially if we introduced an arbitra scale of measurement with 68° Effective Temperatu.. becoming 100.

J. A. C. WILLIAMS, *Associate Fellow.*

In reply to Mr. Williams:—

The object of Fig. 19, dealing with the subject of Effective Temperature Control, was to indicate the effects of humidity, air velocity and clothing on the comfort standard of the average human being.

There are many such charts available today and they all have an arbitrary standard and hence will be different for different people.

It is obvious that the Effective Temperature required for different airline routes will vary.

I would agree with Mr. Williams that the term " Effective Temperature " is misleading but it has become so accepted that it is somewhat difficult to delete such a phrase from our minds and use the more exact description of " Comfort Standard."

E. W. STILL, *Fellow.*

# THE LIBRARY

## *Reviews*

AERONAUTICS AT THE MID-CENTURY. *Jerome C. Hunsaker. Yale University Press 1952. Oxford University Press, London. 116 pp. Photographs and diagrams. 20s.*

In this book which is founded on the Terry Lectures given by the author at Yale in 1951, the growth of aeronautics is surveyed from the time of the Wright Brothers to the present day. It is in three sections, the first of which deals with the technical developments of the past fifty years and traces the advances of knowledge which have produced the vast improvement in aeroplane performance since the Wrights first flew. The second section is entitled " Air Transportation " and considers the various factors involved: economics, safety, airports and a host of other matters. Flying boats, helicopters, private aeroplanes and even rigid airships and blimps are not forgotten. The third section deals with the social and political effects of the advent of world-wide flying and is naturally the most speculative part of the work. Though the whole book is quite short, nothing, and certainly no major point, appears to have been overlooked. The writing is concise, even terse in places, but very readable, and the volume is exceedingly well illustrated with photographs, by no means all of which come from American sources. There are few diagrams and no mathematics or even formulæ! In such a book there are of necessity a great many expressions of opinion and it is quite impossible in a short review even to mention them in any detail, let alone to criticise. Where the opinions of others are quoted, full references are given in footnotes. The author evidently believes that continued and even accelerated progress can be looked for in the years to come in nearly all the fields of endeavour with which he deals. He feels, however, that the once-expected substitution of the private aeroplane for the motor-car is not at all likely to take place. He also doubts that commercial aircraft will enter the supersonic speed range, at least for a very long while, though he fully realises the paramount importance of supersonic flying, even at a high cost in fuel, for the military types of aircraft. He emphasises that the scientific discoveries which have made modern aviation possible, just as in other fields of research, can be used either for good or for evil, and expresses his hope that mankind will turn to reason and elect the good. In this, all his readers will doubtless agree with him. The book, which is his first, will be read with interest by the specialist, but perhaps will prove even more enlightening to the ordinary reader, who wants to obtain, by pleasant reading, a picture of the art and science of aeronautics as it stands at the mid-century.—ERNEST F. RELF.

ANALYTICAL MECHANICS FOR ENGINEERS. *F. B. Seely and Newton E. Ensign. 4th Edition 1952. John Wiley, New York. Chapman & Hall, London. 443 pp. 569 diagrams. Examples and Index. $5.50 net.*

In the Preface to the First Edition, published in 1921, the authors state their aim " to make the principles of mechanics stand out clearly . . . to apply the principles to concrete problems of practical value and to emphasise the physical in addition to the mathematical interpretation of the principles." That the book has run through four editions in the 30 years seems to indicate that the aim has been achieved and more careful perusal supports this view. The book is well printed, contains an abundance of diagrams and problems, and an adequate index.

The traditional division of mechanics into statics, kinematics and kinetics is followed. In statics, much use is made of graphical methods, with emphasis on forces in simply rigid frameworks and bending moments for point-loaded light beams; also the common catenary gets good treatment. Friction has a separate chapter where appear the usual machines, the screw and belt (no mention seems to be made of " mechanical advantage "). Kinematics is given a usual treatment: an unusual feature is the discussion of the motion of a print relative to a rotating body (Coriolis' law).

In the kinetics section, the discussion of units in dealing with Newton's Second Law is distinctly helpful. The use of the " free body " idea, especially in this section (in forming equations of motion) is an aid in clarifying problems. The motion of a rigid body, whether acted upon by forces or by impulses in a plane, is dealt with thoroughly and there is a four-page " paragraph " on the gyroscope which serves as a useful introduction to the subject.

A fourth section, headed " Special Topics," contains chapters on mechanical vibrations (free, undamped; free, with damping proportional to the velocity; freed, without damping), on balancing of rotating masses, and a systematic discussion of First Moments and Moments of Inertia of line, plane area and volume of revolution.

A welcome note in the book is the introduction of three dimensions to both statics and dynamics problems (*e.g.* composition of couples in space by means of vectors; balancing of rotating masses).

There are a few points of criticism. The rather " set " procedure in dynamics of using suffixes on $\Sigma$ notation in force resolution ($\Sigma F_x$, $\Sigma F_n$) may lead to indifferent imitation by the weak student. Prominence is given to the alternative method of analysis using inertia forces: it is doubtful whether this double approach is desirable—it adds to the bulk and may cause confusion. Both the size of the book and its price militate against its use as a text-book by the English student. The wealth of material, both of exposition and of problems to be worked, is rather overwhelming when time presses. It should be a useful addition to a library.—A. J. HATLEY (Imperial College).

LIGHTING IN INDUSTRY. *British Electrical Development Association. Electricity and Productivity Series, No. 2. London 1952. 154 pp. 88 figs. 9s. net.*

The British Electrical Development Association is publishing a series (eight books are planned at the moment) of short textbooks on the application of electricity for the increase of British productivity. This book is number two in that series and is a companion volume to " Materials Handling " (number four) reviewed in January.

There have been nearly seventy British productivity teams visiting America in the past four or five years and in general each has reported, whatever else they may have said, that: (*a*) American productivity is notably higher and

(*b*) America uses several times the electrical horsepower per operative that we do in Britain. Although there is not necessarily proof of causation there is considerable reason to believe that the higher electrical aids constitute an important factor in this ratio. Therefore, these books, carefully compiled with the latest and best practical data available are likely to prove most useful to all who are concerned with productivity.

This small book on lighting, as I judge it, has been written with the following objectives:

(*a*) To provide easily understandable and easily applied practical data.

(*b*) To make it convincing and dramatic and acceptable to the less academic managers; and

(*c*) To give a wide enough set of examples to avoid the famous parrot cry of conservative management " But it won't work in *our* industry."

There are many books on lighting in industry, but I much doubt if any of them have influenced, or will influence, factory management as strongly as this one by virtue of its striking illustration and carefully prepared tabular sheets.

Illumination alone will not put up productivity, but who will deny that " a man works best when he can see what he is doing " is a slogan applicable to most industries.—J. V. CONNOLLY.

THE WONDER BOOK OF AIRCRAFT. *Ward, Lock 1952. 256 pp. Illustrated. 12s. 6d. net.*

Confined exclusively to civil aircraft, and particularly air liners—for a companion book deals with the R.A.F. and service aircraft—a very consistently styled and lucid account is given in non-technical language of every facet of the modern aeroplane arising from its half century of evolution.

For the schoolboy, or indeed anybody having a general interest in flying, this book gives an exceptionally good and comprehensive survey of the problems associated with the design, development and commercial operation of the modern aeroplane, and the manner in which success is being achieved. A bird's-eye view is afforded of the entire great industry of air transport, yet the details stand out equally boldly, for accurate, simple explanation is given of the theory and underlying function, whether of flight itself or the operation of gas turbines, propellers, instruments, the latest radio and navigational aids, and methods of airport control. The concluding chapters neatly bring the story into the personal orbit of the young readers by discussing not only aviation as a career in general, but describing in some detail the technical qualifications and training required for airline pilot and aeroplane designer.

Lavishly illustrated, this new " Wonder Book," modern and topical in presentation, easily outstrips, as the publishers claim, all other " juveniles " dealing with aircraft—and indeed sets a high standard for comparable books, whatever the subject.

We would only seriously dispute with the anonymous author when he says: " Now that romance has gone out of flying. . . ." To have written this book, as the title implies, means he is very well aware that:

" . . . all unseen Romance brought up the nine fifteen."

—H. J. PENROSE.

NUMERICAL ANALYSIS. *D. R. Hartree. Oxford University Press 1952. 287 pp. Index. 31 Figs. 30s. net.*

Computing was not invented during the last war. Nevertheless increasing sophistication of experimental and design techniques has forced a huge expansion of computational activity into fields hitherto relatively innocent of such practices. In the aeronautical world too much of this falls far below the rigorous standards proudly observed in other things. Partly this comes from the lack of guidance; partly from refusal to be guided. Certainly there are few up-to-date texts suitable for engineers and physicists, although the notes issued by the College of Aeronautics and the books of Milne and, in translation, Willers can be recommended.

The present work has the advantages of those mentioned and is also more comprehensive and better connected. Decades of experience of computing and teaching computing inform every section. The author has winnowed away methods differing only in the way they are explained, not in the way they are worked, and also methods due to " armchair computors." " Much could be written," says the author, " about how *not* to do numerical calculations." Much, alas, has been written.

Mathematical topics treated cover the usual range with unusual depth: finite differences and applications; polynomial (but not trigonometrical) interpolation; quadrature; linear systems; polynomial equations; and differential equations, partial and ordinary. The sections on differential equations are outstanding. The final chapter outlines planning of calculations for automatic computers.

To the reviewer the most valuable chapters are the first three. The first deals with fundamentals, such as errors and blunders. The second tries to instill respect for skill in handling the tools of the trade, the main one being the desk calculator. These are unique in that, although costing as much as motor cars, they are sold by and to people who do not know how to use them properly. The book to teach this has yet to be written. In the meantime Professor Hartree may have persuaded some people that slovenliness is nothing to be proud of and has to be paid for.

The third chapter deals with numerical evaluation of formulæ, driving home the lack of connection between typographical convenience and computational efficiency, and the computational differences between formally equivalent expressions. The author could expand these chapters into a separate book to everybody's profit.

To those who do their own computing the book is necessary and sufficient. To professionals who do and organise computation for others it is not sufficient, because the problems are then clerical rather than mathematical, but it remains a pleasant necessity. Everyone of even moderate mathematical literacy will find it interesting and stimulating. Probably it and subsequent revisions will be, like " Whittaker and Robinson," a standard text for decades.—R. A. FAIRTHORNE (Royal Aircraft Establishment).

HIGH-SPEED PHOTOGRAPHY. *George A. Jones. Chapman & Hall. London 1952. 311 pp. 118 figs. Index. 42 net.*

It is in no sense an adverse criticism of this work that I find myself comparing it with Chesterman's *The Photography of Rapid Events* (1951). Indeed, such a comparison was inevitable; the earlier work had earned a well-deserved place in many libraries and any new book dealing with this subject will have that gauntlet to run. Let it be said right away that " High-Speed Photography " is a complementary and not a rival work to the other; each fulfils its own special function extremely well and supplies a need that had been growing acute.

The book under review approaches the subject from a very practical viewpoint; the admittedly wide field is well covered and the author has succeeded in his efforts to weld together broad fundamental theory, practical experience and technical applications. The accounts of equipment design, with continual and almost complete

reference to available apparatus, are outstanding features of the work and the bibliographical references include all those which a research department photographer would have been collecting over the past few years. The various techniques for both still and ciné work are fully dealt with and the behaviour of sensitive materials under short exposure conditions is discussed with commendable clarity.

With such a wide field it was only to be expected that occasionally the specialist would find the section dealing with his own subject a little disappointing; for example, it must be admitted that the coverage of schlieren work is not as complete as the aeronautical research worker might like; indeed, certain of the more important references have been missed completely. These will doubtless be included in the later editions which the book deserves.

To the more general practitioner—the photographer whose work is to bring photography as a tool to be applied wherever suitable to any type of research problem—this work will be both an eye-opener and a standing reference. From exposures of 1/3,000 second to 1/1,000,000 second and frame speeds up to 100,000,000 per second is a range that should satisfy most; after all, few man-made events exceed a speed of $10^5$ metres per second!

Reference might perhaps have been made to two important items of equipment that have recently appeared. The new British 35 mm. rotating-prism ciné camera with synchronous flash recently developed by W. D. Chesterman and others and shown at the British Industries Fair in 1952 is in current production; that purchase of this item would be by sterling and not by dollars is a major consideration these days! The other item is the range of small ciné-film processing machines for both 35 mm. and 16 mm. sizes now being marketed by one of the leading British photographic firms. The possibility or otherwise of "on-site" processing of 100 ft. lengths of film has often been the deciding factor when considering high-speed cinématography as a solution to a particular problem, and many of the items of camera equipment mentioned in this work would be the more readily used if the results they produce could be available within an hour or less. This is now possible at a much cheaper price than hitherto and it is only fair that this should be stated here; the finest book on "how-to-get-high-speed-pictures" may sometimes be purely academic if one has to wait for a day or so for each experimental result!—C. A. GUTHRIE, A.R.P.S.

AIRCRAFT STRUCTURAL MECHANICS. *F. R. Steinbacher and G. Gerard. Pitman. London 1952. 346 pp. Diagrams. 35s. net.*

It is a pleasure to welcome a book which covers the basic mechanics of the problems which are the particular lot of the aircraft structural engineer. This book is certainly written for the *aircraft* engineer, and is written at a level which will make it useful to anyone trying to achieve a knowledge of what is essential in this profession. The level is not too high, in that it will not present any great difficulty to the student who has acquired a familiarity with the elements of Strength of Materials; yet the ground finally covered is gratifyingly extensive.

There are three main divisions to the work: firstly, the more-or-less "standard" bending-torsion theory of beams and analysis of indeterminate structures; then a consideration of the shear flow in thin-web beams and in shells, and finally a proportionately lengthy section on buckling problems.

It is this last section which commends the book. The topics covered include elastic and plastic buckling of columns and flat plates, local instability of columns and stringer-skin combinations, and the section closes with a very complete chapter on the design of shear beams which includes the treatment of fully-developed and incomplete tension fields. A wealth of material is gathered together here and presented clearly and simply, and for this section alone the book is well worth buying.

The central section examines the relation between shear flow and end-load in thin beams and simple shells, considers the torsion of shells and proceeds to the torsion of statically indeterminate shell structures.

To the reviewer the first section is the weakest part of the whole work. It reads as if the authors felt that they had an obligation to include it but have not been greatly interested. They have tried to be a little "different," but this has not been conspicuously successful. One may look in vain for mention of Castigliano or his theorems.

This apparent lack of enthusiasm seems to be reflected in a certain carelessness in the setting of examples. Thus in problem 3.3 all the relevant numerical quantities are given except for the value of *EI*. Again, the diagrams are well drawn, but not always as accurate or as clear as they might be. An error which may be noted is that equation (3.17) contains a superfluous *x*.

These slight criticisms apart, this book may be heartily recommended as an extremely valuable addition to the library of the budding stressman; and for that reason one may deplore that current production costs make such a book so expensive.—K. H. GRIFFIN (College of Aeronautics).

TEACH YOURSELF TO FLY. *Nigel Tangye. Revised by D. H. MacBeath. English Universities Press 1952. 128 pp. Illustrated. 6s. net.*

It is somewhat ironic that *Teach Yourself to Fly* should be published coincidentally with the closure of thirty British flying training schools. However, as explained by the original author, the title is not intended to be taken literally in this modern world of regulations, permits and licences.

First published in 1938, the book is advertised as re-written and brought up to date under the auspices of the Guild of Air Pilots and Air Navigators. This ought to be sufficient guarantee of its worth, but nevertheless it is in fact by no means the best of its class, though possibly the only one now available. Though its purpose is commendable, numerous errors mar it, and better use should have been made of diagrams.

The potential pilot may be a little bewildered on being told at one moment to "relax—relax," only to be informed that "great patience and a will of iron are necessary." Instinct is described as "a fickle jade" to be ignored, yet the pupil is exhorted to "maintain the correct rate of turn by your sense of balance." He may find this peculiarly difficult if he believes the up-going aileron increases "drag as well as *lift*," particularly if he gets an instability arising from "failure to compensate in wing or aileron adjustment for the torque of the motor."

One would suspect that, unable to eliminate the individualistic touch of Tangye, the G.A.P.A.N. have brought the book up to date merely by substituting relevant details of a Chipmunk for the Moth on which the instruction was originally based. It is a pity, for a good book at this price might inspire youth to fly if the Government would help with facilities.—H. J. PENROSE.

AIR PILOT TRAINING. *Bert A. Shields. McGraw Hill Book Company Inc. 1952. 800 pp. Price 64s. net.*

Since starting to review this 800 page volume, I have had, sculling about in my mind, a half-remembered quotation which goes something like this:—

" And the wonder grew and grew
That one small head could contain all he knew."

If ever there was an author to whom those two lines could genuinely apply it is surely Mr. Bert A. Shields.

" Air Pilot Training " is not so much a book as a one volume encyclopedia, and any pilot knowing all that is set out within its covers would be a combination of Don Bennett, Captain Majendie, Laurence Pritchard and Sydney Camm.

There are profusely illustrated chapters on building an aeroplane; the materials involved; the principles of flight; the intimate working of the instruments, and, almost as a by-product, how to fly it when built.

The reader is then led into a whole section on aircraft engines, propellers, and instrumentation, from the Otto Cycle to the anatomy of axial flow. Then, with scarcely a pause, we are amid the intricacies of navigation, from Bradshaw to the Equation of Time, via every sort of Radio Aid. Finally, there is a whole sequence on Meteorology, starting with the elementary physics of gases, and ending with Pressure Pattern flight paths.

This new volume is the fourth edition of a work which must compel admiration. One can hardly imagine any day-to-day question, either of theory or of practical fact, which Mr. Shields doesn't deal with somewhere. There is a thorough index, which is, indeed, most necessary.

This is not a book to sit and read, any more than one sits and reads the *Encyclopedia Britannica*, but as a concise Reference it is almost unrivalled. The bias, throughout, is naturally American, but due credit is given to Britain for pioneer flights such as that of Alcock and Brown, and to Frank Whittle for the turbo-jet.

The illustration, both by photograph and sketch, is so thorough, that there is hardly a page which does not have at least three pictures of one kind or another. The " examination papers " at the end of each of the 37 chapters must surely reveal deserts of ignorance in the most learned of us. The reviewer would class this book as almost a " must " for the serious student.—CHARLES GARDNER.

NEWNES ENGINEER'S REFERENCE BOOK. *Edited by F. J. Camm. George Newnes Ltd., London 1952. 1,909 pp. Illustrations. Index. Fifth Edition. 63s. net.*

In the fifth edition of this comprehensive work, a miscellany of material included at the end of the previous edition has been absorbed into the appropriate sections of the book. At the same time the opportunity has been taken to improve the arrangement and to bring the subject matter up-to-date by the inclusion of data on recently developed materials, tools and processes. An omission in previous editions has been rectified, although perhaps somewhat inadequately, by the addition of a section on mechanics.

Of the information on materials included for the first time, the section on modern alloy steels is especially useful; also the data on bonded asbestos for bearings and on cerromatrix for use in presswork.

On the subject of measurement there is new matter on taper gauges and gear teeth as well as a table of sine bar setting constants.

The rapid developments in machine tools calls for constant review of the relevant sections in a book of this kind. In this connection, additions cover gear cutting, broaching, single spindle automatics, die sinking and modern milling practice. In these and other numerous additions the high standard of this work has been well maintained.—H. C. SMITH.

WORLD AIRLINE RECORD, 1952 EDITION. *Roy R. Roadcap and Associates, Chicago 1952. 400 pp. Maps and diagrams. $9.75.*

This is the fourth annual edition of the record, which now calls itself the " Standard Reference of the Industry," that is, air transport. The new edition has been greatly expanded, covering now 240 airlines in six continents. There are 40 traffic density maps, many of them new, and an analysis of density factors, which is intended to give a comparison of relative operating efficiency.

In a standard reference book one looks first of all for accurate and up-to-date information. This seems to have been achieved for the U.S.A. airlines, but not always for the rest. Turning to B.E.A., one finds N. E. Rowe still listed as Controller of Research and Special Development, although the historical section has been carried on to the introduction of the Elizabethan class in the summer of 1952. Under B.O.A.C. there appears a Series II Comet, which is obviously the Mark II. The title of the Russian airline, information on which appears for the first time in this volume, is misspelt, and the data do not agree with what has been published elsewhere, although their reliability cannot be checked, since the origin is not stated.

An annoying feature is the lack of uniformity in the spelling of place names. The illustrations could be condensed with advantage, six photographs of Constellations and three of D.C.-3's do not add much useful information. The space so saved might be used to give a more detailed analysis of operating efficiency data. The present factors, which lump together all the aircraft of widely different types flown by one airline, do not provide a fair or enlightening basis for comparison.—E. PRIBRAM.

# *Additions to the Library*

Ambrose, Capt. L. R. A BRIEF OUTLINE OF INDIAN OCEAN OPERATIONS. Qantas Empire Airways Ltd. 1945.

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Kuchemann, W. and J. Weber. AERODYNAMICS OF PROPULSION. McGraw Hill. 1953.

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Morley, A. W. AIRCRAFT PROPULSION. Longmans Green. 1953.

National Bureau of Standards. LOW TEMPERATURE PHYSICS. U.S.G.P.O. 1952.

Pröll, A. GRUNDLAGEN DER AEROMECHANIK UND FLUGMECHANIK. Springer. 1951.

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Sternberg, E. (*Editor*). PROCEEDINGS OF THE FIRST U.S. NATIONAL CONGRESS OF APPLIED MECHANICS. A.S.M.E. 1952.

U.S. Air Force, Navy, Civil. CLIMATIC AND ENVIRONMENTAL CRITERIA FOR AIRCRAFT DESIGN. A.N.C.22. U.S.G.P.O. 1952.

# Reports

## AERODYNAMICS

### Boundary Layer

*The laminar boundary layer in slip flow. T. Nonweiler. College of Aeronautics, Cranfield. Report No.* 62.

This report discusses the effects of the existence of a small, but finite, molecular mean-free-path on the steady air flow in the laminar boundary layer. The boundary conditions at the exposed surface are modified by the existence of a slip velocity and temperature-jump between the air and the surface, and a theory of first-order approximation is developed to account for the consequent modification to the shear stress and heat flux to the surface.—(1.1).

*Average skin-friction drag coefficients from tank tests of a parabolic body of revolution (N.A.C.A. RM-10). E. J. Mottard and J. D. Loposer. N.A.C.A. T.N.*2854.

Average skin-friction drag coefficients were obtained from boundary-layer total-pressure measurements on a parabolic body of revolution (N.A.C.A. RM-10) basic fineness ratio 15 in water at Reynolds numbers from $4{\cdot}4 \times 10^6$ to $70 \times 10^6$. The tests were made in the Langley tank No. 1 with the body sting-mounted at a depth of two maximum body diameters.—(1.1).

### Compressible Flow

*The laminar boundary layer associated with the retarded flow of a compressible fluid. C. R. Illingworth. A.R.C. R. & M.* 2590.

Two aspects of the solution of the equations governing steady gas flow in a laminar boundary layer, when the main stream velocity is non-uniform, are considered. In the first place it is shown that the equations can be reduced to ordinary differential equations, whose solution implies the similarity of the distributions of velocity and temperature in planes perpendicular to the boundary, only in the case when the main stream velocity is uniform. In the second part, an extension of Pohlhausen's method is used to determine the point of separation of the boundary layer in an air flow in which the pressure increases with a uniform gradient.—(1.2 × 1.1).

*The method of characteristics for the determination of supersonic flow over bodies of revolution at small angles of attack. A. Ferri. N.A.C.A. Report* 1044.

The method of characteristics has been applied to rotational supersonic flow around bodies of revolution at a small angle of attack. The practical numerical calculations are similar to those for zero angle of attack. A method for determining supersonic flow around circular cones at an angle of attack is also given.—(1.2).

*Supersonic flow around circular cones at angles of attack. A. Ferri. N.A.C.A. Report* 1045.

The properties of conical flow without axial symmetry are analysed. The flow around cones of circular cross section at small angles of attack is determined by considering correctly the effect of the entropy gradients in the flow.—(1.2).

*Interaction between a supersonic stream and a parallel subsonic stream bounded by fluid at rest. H. S. Ribner and E. L. Arnoff. N.A.C.A. Technical Note* 2860.

Tsien and Finston's simplified model of shock boundary-layer interaction is modified to introduce effects of the separated " dead-air " bubble, where one exists.—(1.2).

*Convection of a pattern of vorticity through a shock wave. H. S. Ribner. N.A.C.A. T.N.*2864.

An arbitrary weak spatial distribution of vorticity can be represented in terms of plane sinusoidal shear waves of all orientations and wave lengths (Fourier integral). The analysis treats the passage of a single representative weak shear wave through a plane shock and shows refraction and modification of the shear wave with simultaneous generation of an acoustically intense sound wave. Applications to turbulence and to noise in supersonic wind tunnels are indicated.—(1.2).

### Control Surfaces

*Equations and charts for the rapid estimation of hinge-moment and effectiveness parameters for trailing-edge controls having leading and trailing edges swept ahead of the Mach lines. K. L. Goin. N.A.C.A. Report* 1041.

Existing conical-flow solutions have been used to calculate the characteristics of deflected trailing-edge controls located either at the wing tip or far enough inboard to prevent the outermost Mach lines from the controls from crossing the wing tip. For either location, the controls have been assumed to be located far enough outboard to prevent the innermost Mach lines from crossing the wing-root chord. The method for determining control hinge moment resulting from wing angle-of-attack loading is restricted to wings having leading edges swept ahead of the Mach lines. Also included is an approximate method by which the theoretical characteristics may be corrected for aerofoil-section thickness.—(1.3).

### Fluid Dynamics

*The method of influence factors in arithmetical solutions of certain field problems. Part I, A. Thom. Part II, Laura Klanfer. A.R.C. R. & M.* 2440.

This paper gives an extension to the squares method of solving certain field problems. This enables certain problems to be solved without squaring and reduces the actual arithmetical work in others to a fraction of that otherwise required. As an example, the effect of the channel walls is calculated for the flow of a compressible fluid past given profiles in channels of different widths. A comparison is also made of the resulting blockage factor with the values given by the mass flow method described in previous work.—(1.4).

*Spiral motions of viscous fluids. G. Hamel. N.A.C.A. T.M.*1342.

Exact solutions of the steady incompressible viscous flow equations are obtained. The streamlines corresponding to such solutions are in general logarithmic spirals. The more specific cases of purely concentric and purely radial flows are fully investigated. Corresponding to the radial flows are the physically important cases of flow in radially convergent channels and in divergent channels. A second method is used to investigate exact steady and unsteady two-dimensional motions in free spirals. Neighbourhood solutions to the radial flow are also discussed.—(1.4).

*General correlation of temperature profiles downstream of a heated air jet directed at various angles to air stream. R. S. Ruggeri. N.A.C.A. Technical Note* 2855.

An experimental investigation was conducted to determine the temperature profile downstream of a heated-air jet directed at various angles to an air stream. A method is presented which yields a good approximation of the temperature profile in terms of dimensionless parameters of the flow and geometric conditions.—(1.4 × 34.3).

### Internal Flow

*Method of analysis for compressible flow through mixed-flow centrifugal impellers of arbitrary design. J. T. Hamrick, A. Ginsburg and W. M. Osborn. N.A.C.A. Report* 1082.

A method is presented for the analysis of compressible flow between the hub and the shroud of mixed-flow impellers of arbitrary design. Axial symmetry was assumed, but the forces in the meridional (hub-shroud) plane, which are derived from tangential pressure gradients, were taken into account. The method was applied to an experimental mixed-flow impeller.—(1.5 × 27.1).

NOTE:—*The figures in parentheses at the end of each summary are for office use only.*

### Performance Estimation

*Analysis of the effects of boundary-layer control on the take-off and power-off landing performance characteristics of a liaison type of airplane. E. A. Horton, L. K. Loftin, Jr., S. F. Racisz and J. H. Quinn, Jr. N.A.C.A. Report* 1057.

An investigation has been made to determine whether boundary-layer control by suction might reduce the minimum take-off and landing distance of a four-place or five-place aeroplane or a liaison type of aeroplane having a payload of 1,500 lb. and a flight duration of 5 hours.—(1.7 × 1.1).

### Stability and Control

*A generalised treatment of manœuvrability. J. R. Baxter. A.R.L. Australia Report A.*76.

The significance of the idealised constant speed manœuvre in relation to various practical manœuvres has been briefly discussed with reference to earlier work by D. J. Lyons. The equations for idealised manœuvres with "stick fixed" and "stick free" have been developed from the normal equations of aircraft stability by the application of the Laplace Transformation. In this manner they are obtained in a form that is sufficiently general for application to both conventional and tailless aircraft.—(1.8).

*The concept of longitudinal static stability. J. J. Thompson. R.A.A.F. Technical Note Aero No.* 9.

In Part 1, the term "static stability" is discussed, and the conclusion reached that its meaning is given only by its place in the mathematical theory of stability, assuming small displacements from an equilibrium state. Only in particular cases is it possible to give an adequate physical description and relate it to the feel of the aircraft. In general, static stability depends on the constant term in the stability polynomial, and this term also arises from the equations governing the steady state control characteristics. Part 2 is therefore concerned with formulation, in terms of the general theory of aircraft stability, the relations between elevator angle, C.G. position, forward speed, etc., as a basis for the measurement of static stability by flight testing.—(1.8).

*A theoretical method of analyzing the effects of yaw-damper dynamics on the stability of an aircraft equipped with a second-order yaw damper. A. A. Schy and O. B. Gates, Jr. N.A.C.A. Technical Note* 2857.

A method is presented for analysing the effects of autopilot gain, natural frequency, and damping ratio on the damping of an aircraft equipped with a second-order autopilot. The method is illustrated by analysing the effects of a second-order yaw damper on the lateral motion of an aeroplane.—(1.8).

### Wings and Aerofoils

*Aerodynamic coefficients of an oscillating aerofoil with a pressure-seal balanced aileron. A. I. van de Vooren and J. Yff. N.L.L. Amsterdam. Report F.*115.

The presence of a pressure-seal balanced aileron at an oscillating wing causes alterations in some of the non-stationary aerodynamic coefficients. These additional coefficients have been calculated by aid of the ordinary non-stationary aerodynamic theory.—(1.10 × 1.3).

*Graphical solution of Multhopp's equations for the lift distribution of wings. F. Vandrey. Current Paper* 96.

A simple graphical method is described facilitating the determination of the lift-distribution of wings. The basis is Multhopp's method of replacing approximately the integro-differential equation for the circulation by a finite system of linear equations which give the values of the circulation at certain fixed points along the span.—(1.10).

*Swept-wing loading. A critical comparison of four subsonic vortex sheet theories. H. C. Garner. Current Paper* 102.

From a systematic series of calculations of swept-wing loading the writer has formed an opinion of the accuracy and most useful application of vortex lattice theory and the vortex sheet theories of Weissinger, Multhopp and Küchemann. The results provide a general picture of the effect of sweep and compressibility on lift slope and aerodynamic centre.—(1.10).

*Some effects of Reynolds number on a cambered wing at high subsonic Mach numbers. H. E. Gamble. Current Paper* 103.

An untapered, swept-back wing of aspect ratio 4, sweep-back 25° and section 12 per cent. thick (R.A.E. 104 with 1 per cent. camber, $a=0{\cdot}6$) was tested in the R.A.E. high-speed tunnel. The pressure distribution was measured at the mid-semi-span section at various Mach numbers up to 0·88 at Reynolds numbers of 0·8, 1·8 and $3{\cdot}5\times10^6$.—(1.10).

*The effect of endplates on swept wings. D. Küchemann and D. J. Kettle. Current Paper* 104.

Existing methods of calculating the effect of endplates on straight wings are modified so as to apply to swept wings. The changes in overall lift and drag, and also the spanwise distribution of the additional load, can be calculated. The theoretical results are compared with experimental results obtained on swept wings, including new measurements of lift, drag and pitching moment, made on an untapered 45° swept-back wing of aspect ratio 3 at low speed. The method of calculation is also extended to cover the effect of the tip vortex which is formed on wings without endplates.—(1.10).

*Theoretical study of the transonic lift of a double-wedge profile with detached bow wave. W. G. Vincenti and C. B. Wagoner. N.A.C.A. Technical Note* 2832.

Numerical calculations are described of the aerodynamic characteristics at small angle of attack of a thin, doubly symmetrical, double-wedge profile in the range of supersonic flight speed in which the bow wave is detached. The analysis is carried out within the framework of the transonic (non-linear) small-disturbance theory.—(1.10).

*Section characteristics of a* 10·5 *per cent. thick airfoil with area suction as affected by chordwise distribution of permeability. R. E. Dannenberg and J. A. Weiberg. N.A.C.A. Technical Note* 2847.

Results are presented of an investigation of a two-dimensional, 10·5 per cent. thick symmetrical aerofoil with area suction near the leading edge. Area suction delayed leading-edge stall. The suction flow and power coefficients required to maintain a given lift are shown to be dependent on the chordwise extent and the porosity and permeability arrangement of the surface material. The flow-resistance characteristics of several porous materials are presented.—(1.10).

*Supersonic wave drag of non-lifting delta wings with linearly varying thickness ratio. A. Henderson, Jr. N.A.C.A. Technical Note* 2858.

The supersonic wave drag of a non-lifting, symmetrical, double-wedge-profile, delta wing the thickness ratio of which varies linearly in the spanwise direction is calculated by means of linear theory. The thickness distributions for minimum drag and the corresponding values of the ratio of the drag of a linearly varying thickness-ratio wing to a constant-thickness-ratio wing are found.—(1.10).

*Analytical investigation of icing limit for diamond-shaped airfoil in transonic and supersonic flow. E. E. Callaghan and J. S. Serafini. N.A.C.A. T.N.* 2861.

Calculations have been made for the icing limit of a diamond aerofoil at zero angle of attack in terms of the stream Mach number, stream temperature, and pressure altitude. The icing limit is defined as a wetted-surface temperature of 32° F. and is related to the stream conditions by the method of Hardy. The results show that the point most likely to ice on the aerofoil lies immediately behind the shoulder and is subject to possible icing at Mach numbers as high as 1.4.—(1.10).

### Testing and Instruments

*A frost point hygrometer for supersonic wind tunnels. D. Beastall and A. Winyard. Current Paper* 106.

This note describes a frost point hygrometer suitable for measuring the water vapour content of the air in supersonic wind tunnels at any stagnation pressure within their present range of operation. It uses $CO_2$ as a coolant and is economical in construction and operation.—(1.12).

*X-ray instrumentation for density measurements in a supersonic flow field. J. Dimeff, R. K. Hallett, Jr., and C. F. Hansen. N.A.C.A. T.N.* 2845.

An instrument has been constructed to measure the density of an air stream by utilising the reduction in intensity of an undeviated beam of X-rays. This equipment has been designed for density ranges from $2\times10^{-5}$ to $3\times10^{-4}$ grams per cubic centimetre. Path-length-density products were measured within $5\times10^{-5}$ g/cm² for X-ray-beam areas of $5\times10^{-4}$ cm² and averaging times of 30 seconds, and within $1\times10^{-5}$ g/cm² for beam areas of $8\times10^{-3}$ cm² and averaging times of 5 minutes.—(1.12).

*Corrections for lift, drag, and moment of an airfoil in a supersonic tunnel having a given static pressure gradient. H. F. Ludloff and M. B. Friedman. N.A.C.A. Technical Note* 2849.

Corrections for lift, drag and moments of a two-dimensional aerofoil are analysed assuming that the aerofoil is tested in a supersonic tunnel in which the pressure field, instead of being uniform, is characterised by gradients in the axial and transverse directions.—(1.12).

## AEROELASTICITY

*Steady vibrations of wing of circular plan form and theory of wing of circular plan form. N. E. Kochin. N.A.C.A. T.M.* 1324.

This paper treats the problem of determining the lift, moment, and induced drag of a thin wing of circular plan form in uniform incompressible flow on the basis of linearised theory. As contrasted to a similar paper by Kinner, in which the acceleration potential method was used, the present paper utilises the concept of the velocity potential. Calculations of the lift and moment are presented for several deformed shapes.—(2.0).

## AIRCRAFT DESIGN

### Landplanes

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## STRUCTURES

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*The stressing of simple rings J. Solvey. A.R.L. Australia. Structures and Materials Monograph* 2.

This report, which is more in the nature of a review than of an investigation, deals with the stressing of simple rings loaded in their own plane. As far as could be ascertained from the available literature, it covers all existing methods. These methods are classified, and accompanied by a critical analysis of their usefulness. Several examples are worked out in detail, using each method in turn, thus illustrating various aspects of that analysis. Recommendations as to the use of each particular method are given, so enabling the designer to choose the most advantageous stressing procedure for any shape of ring and type of loading.—(33.2.4).

*An estimate of the accuracy of Denke's method of spar stress analysis. B. F. Garland. A.R.L. Australia. Structures and Materials Note* 200.

Denke's method has been applied to over two hundred test results in order to check its accuracy. A comparison between the measured and the predicted stresses shows that the method is fairly accurate in predicting diagonal tensile stresses in the web, and average compressive stresses in the stiffeners; but it is not accurate enough in predicting compressive stresses in flanges or maximum fibre stresses in stiffeners.—(33.2.4).

## THERMODYNAMICS

THERMODYNAMIC PROPERTIES

*Combustion in the gas turbine. A survey of war-time research and development. P. Lloyd. R. & M.* 2579.

The present report attempts a general survey of the whole field of gas-turbine combustion. The report covers both research and development, and while it is mainly concerned with British work, some mention is also made of German work on the same subject. The related processes of combustion in propulsive ducts are briefly touched on. The report is based on a paper to the Institution of Mechanical Engineers, but with much fresh material, including a comprehensive bibliography.—(34.1.1).

*Constantes thermodynamiques des gaz aux températures élevées. M. G. Ribaud. Publications Scientifiques et Techniques du Ministère de L'Air, France, No.* 266.—(34.1).

*Investigation of spontaneous ignition temperatures of organic compounds with particular emphasis on lubricants. C. E. Frank, A. U. Blackham and D. E. Swarts. N.A.C.A. Technical Note* 2848.

The study of spontaneous ignition characteristics of organic compounds has been extended to include various types of lubricants by using a spray-injection as well as a dropwise-addition procedure.—(34.1.1).

NOTE:—The Accessories list of the Science Museum Library for 3rd January 1953 includes "United States: National Advisory Committee for Aeronautics" Technical Note 2567 and onwards. The Library reference is TU 5888 B.Q.

READY IN APRIL

# THE AERONAUTICAL QUARTERLY

Volume IV FEBRUARY 1953 Part II

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On the Noise Emanating from a Two-Dimensional Jet Above the Critical Pressure — *Alan Powell*

Some Aspects of Laminar Boundary Layer Separation in Compressible Flow with no Heat Transfer to the Wall — *G. E. Gadd*

Buckling of Oblique Plates with Clamped Edges Under Uniform Compression — *W. H. Wittrick*

A Note on the Theory of the Constant-Area Mixing of Compressible Flows as Applied to High-Speed Wind Tunnel Design — *F. G. Irving*

A Note on the Performance of Ducted Fans — *Bryan Thwaites*

On the Resistance of Screens — *K. E. G. Wieghardt*

Flow Changes in Gases in which Mass and Impulse are Conserved — *L. G. Dawson*

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PERFORMANCE ESTIMATION

*Analysis of the effects of boundary-layer control on the take-off and power-off landing performance characteristics of a liaison type of airplane. E. A. Horton, L. K. Loftin, Jr., S. F. Racisz and J. H. Quinn, Jr. N.A.C.A. Report* 1057.

An investigation has been made to determine whether boundary-layer control by suction might reduce the minimum take-off and landing distance of a four-place or five-place aeroplane or a liaison type of aeroplane having a payload of 1,500 lb. and a flight duration of 5 hours.—(1.7 × 1.1).

STABILITY AND CONTROL

*A generalised treatment of manœuvrability. J. R. Baxter. A.R.L. Australia Report A.*76.

The significance of the idealised constant speed manœuvre in relation to various practical manœuvres has been briefly discussed with reference to earlier work by D. J. Lyons. The equations for idealised manœuvres with "stick fixed" and "stick free" have been developed from the normal equations of aircraft stability by the application of the Laplace Transformation. In this manner they are obtained in a form that is sufficiently general for application to both conventional and tailless aircraft.—(1.8).

*The concept of longitudinal static stability. J. J. Thompson. R.A.A.F. Technical Note Aero No.* 9.

In Part 1, the term "static stability" is discussed, and the conclusion reached that its meaning is given only by its place in the mathematical theory of stability, assuming small displacements from an equilibrium state. Only in particular cases is it possible to give an adequate physical description and relate it to the feel of the aircraft. In general, static stability depends on the constant term in the stability polynomial, and this term also arises from the equations governing the steady state control characteristics. Part 2 is therefore concerned with formulation, in terms of the general theory of aircraft stability, the relations between elevator angle, C.G. position, forward speed, etc., as a basis for the measurement of static stability by flight testing.—(1.8).

*A theoretical method of analyzing the effects of yaw-damper dynamics on the stability of an aircraft equipped with a second-order yaw damper. A. A. Schy and O. B. Gates, Jr. N.A.C.A. Technical Note* 2857.

A method is presented for analysing the effects of autopilot gain, natural frequency, and damping ratio on the damping of an aircraft equipped with a second-order autopilot. The method is illustrated by analysing the effects of a second-order yaw damper on the lateral motion of an aeroplane.—(1.8).

WINGS AND AEROFOILS

*Aerodynamic coefficients of an oscillating aerofoil with a pressure-seal balanced aileron. A. I. van de Vooren and J. Yff. N.L.L. Amsterdam. Report F.*115.

The presence of a pressure-seal balanced aileron at an oscillating wing causes alterations in some of the non-stationary aerodynamic coefficients. These additional coefficients have been calculated by aid of the ordinary non-stationary aerodynamic theory.—(1.10 × 1.3).

*Graphical solution of Multhopp's equations for the lift distribution of wings. F. Vandrey. Current Paper* 96.

A simple graphical method is described facilitating the determination of the lift-distribution of wings. The basis is Multhopp's method of replacing approximately the integro-differential equation for the circulation by a finite system of linear equations which give the values of the circulation at certain fixed points along the span.—(1.10).

*Swept-wing loading. A critical comparison of four subsonic vortex sheet theories. H. C. Garner. Current Paper* 102.

From a systematic series of calculations of swept-wing loading the writer has formed an opinion of the accuracy and most useful application of vortex lattice theory and the vortex sheet theories of Weissinger, Multhopp and Küchemann. The results provide a general picture of the effect of sweep and compressibility on lift slope and aerodynamic centre.—(1.10).

*Some effects of Reynolds number on a cambered wing at high subsonic Mach numbers. H. E. Gamble. Current Paper* 103.

An untapered, swept-back wing of aspect ratio 4, sweep-back 25° and section 12 per cent. thick (R.A.E. 104 with 1 per cent. camber, $a=0{\cdot}6$) was tested in the R.A.E. high-speed tunnel. The pressure distribution was measured at the mid-semi-span section at various Mach numbers up to 0·88 at Reynolds numbers of 0·8, 1·8 and $3{\cdot}5\times10^6$.—(1.10).

*The effect of endplates on swept wings. D. Küchemann and D. J. Kettle. Current Paper* 104.

Existing methods of calculating the effect of endplates on straight wings are modified so as to apply to swept wings. The changes in overall lift and drag, and also the spanwise distribution of the additional load, can be calculated. The theoretical results are compared with experimental results obtained on swept wings, including new measurements of lift, drag and pitching moment, made on an untapered 45° swept-back wing of aspect ratio 3 at low speed. The method of calculation is also extended to cover the effect of the tip vortex which is formed on wings without endplates.—(1.10).

*Theoretical study of the transonic lift of a double-wedge profile with detached bow wave. W. G. Vincenti and C. B. Wagoner. N.A.C.A. Technical Note* 2832.

Numerical calculations are described of the aerodynamic characteristics at small angle of attack of a thin, doubly symmetrical, double-wedge profile in the range of supersonic flight speed in which the bow wave is detached. The analysis is carried out within the framework of the transonic (non-linear) small-disturbance theory.—(1.10).

*Section characteristics of a* 10·5 *per cent. thick airfoil with area suction as affected by chordwise distribution of permeability. R. E. Dannenberg and J. A. Weiberg. N.A.C.A. Technical Note* 2847.

Results are presented of an investigation of a two-dimensional, 10·5 per cent. thick symmetrical aerofoil with area suction near the leading edge. Area suction delayed leading-edge stall. The suction flow and power coefficients required to maintain a given lift are shown to be dependent on the chordwise extent and the porosity and permeability arrangement of the surface material. The flow-resistance characteristics of several porous materials are presented.—(1.10).

*Supersonic wave drag of non-lifting delta wings with linearly varying thickness ratio. A. Henderson, Jr. N.A.C.A. Technical Note* 2858.

The supersonic wave drag of a non-lifting, symmetrical, double-wedge-profile, delta wing the thickness ratio of which varies linearly in the spanwise direction is calculated by means of linear theory. The thickness distributions for minimum drag and the corresponding values of the ratio of the drag of a linearly varying thickness-ratio wing to a constant-thickness-ratio wing are found.—(1.10).

*Analytical investigation of icing limit for diamond-shaped airfoil in transonic and supersonic flow. E. E. Callaghan and J. S. Serafini. N.A.C.A. T.N.* 2861.

Calculations have been made for the icing limit of a diamond aerofoil at zero angle of attack in terms of the stream Mach number, stream temperature, and pressure altitude. The icing limit is defined as a wetted-surface temperature of 32° F. and is related to the stream conditions by the method of Hardy. The results show that the point most likely to ice on the aerofoil lies immediately behind the shoulder and is subject to possible icing at Mach numbers as high as 1.4.—(1.10).

TESTING AND INSTRUMENTS

*A frost point hygrometer for supersonic wind tunnels. D. Beastall and A. Winyard. Current Paper* 106.

This note describes a frost point hygrometer suitable for measuring the water vapour content of the air in supersonic wind tunnels at any stagnation pressure within their present range of operation. It uses $CO_2$ as a coolant and is economical in construction and operation.—(1.12).

*X-ray instrumentation for density measurements in a supersonic flow field. J. Dimeff, R. K. Hallett, Jr., and C. F. Hansen. N.A.C.A. T.N.* 2845.

An instrument has been constructed to measure the density of an air stream by utilising the reduction in intensity of an undeviated beam of X-rays. This equipment has been designed for density ranges from $2 \times 10^{-5}$ to $3 \times 10^{-4}$ grams per cubic centimetre. Path-length-density products were measured within $5 \times 10^{-5}$ g/cm² for X-ray-beam areas of $5 \times 10^{-4}$ cm² and averaging times of 30 seconds, and within $1 \times 10^{-5}$ g/cm² for beam areas of $8 \times 10^{-3}$ cm² and averaging times of 5 minutes.—(1.12).

*Corrections for lift, drag, and moment of an airfoil in a supersonic tunnel having a given static pressure gradient. H. F. Ludloff and M. B. Friedman. N.A.C.A. Technical Note* 2849.

Corrections for lift, drag and moments of a two-dimensional aerofoil are analysed assuming that the aerofoil is tested in a supersonic tunnel in which the pressure field, instead of being uniform, is characterised by gradients in the axial and transverse directions.—(1.12).

## AEROELASTICITY

*Steady vibrations of wing of circular plan form and theory of wing of circular plan form. N. E. Kochin. N.A.C.A. T.M.* 1324.

This paper treats the problem of determining the lift, moment, and induced drag of a thin wing of circular plan form in uniform incompressible flow on the basis of linearised theory. As contrasted to a similar paper by Kinner, in which the acceleration potential method was used, the present paper utilises the concept of the velocity potential. Calculations of the lift and moment are presented for several deformed shapes.—(2.0).

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A numerical method is presented for the stress analysis of stiffened-shell structures of arbitrary cross section under non-uniform temperature distributions. The method is based on a previously published procedure that is extended to include temperature effects and multi-cell construction. The application of the method to practical problems is discussed and an illustrative analysis is presented of a two-cell box beam under the combined action of vertical loads and a non-uniform temperature distribution. This report was formerly T.N.2241.—(33.2.2).

*The stressing of simple rings J. Solvey. A.R.L. Australia. Structures and Materials Monograph* 2.

This report, which is more in the nature of a review than of an investigation, deals with the stressing of simple rings loaded in their own plane. As far as could be ascertained from the available literature, it covers all existing methods. These methods are classified, and accompanied by a critical analysis of their usefulness. Several examples are worked out in detail, using each method in turn, thus illustrating various aspects of that analysis. Recommendations as to the use of each particular method are given, so enabling the designer to choose the most advantageous stressing procedure for any shape of ring and type of loading.—(33.2.4).

*An estimate of the accuracy of Denke's method of spar stress analysis. B. F. Garland. A.R.L. Australia. Structures and Materials Note* 200.

Denke's method has been applied to over two hundred test results in order to check its accuracy. A comparison between the measured and the predicted stresses shows that the method is fairly accurate in predicting diagonal tensile stresses in the web, and average compressive stresses in the stiffeners; but it is not accurate enough in predicting compressive stresses in flanges or maximum fibre stresses in stiffeners.—(33.2.4).

## THERMODYNAMICS

THERMODYNAMIC PROPERTIES

*Combustion in the gas turbine. A survey of war-time research and development. P. Lloyd. R. & M.* 2579.

The present report attempts a general survey of the whole field of gas-turbine combustion. The report covers both research and development, and while it is mainly concerned with British work, some mention is also made of German work on the same subject. The related processes of combustion in propulsive ducts are briefly touched on. The report is based on a paper to the Institution of Mechanical Engineers, but with much fresh material, including a comprehensive bibliography.—(34.1.1).

*Constantes thermodynamiques des gaz aux températures élevées. M. G. Ribaud. Publications Scientifiques et Techniques du Ministère de L'Air, France, No.* 266.—(34.1).

*Investigation of spontaneous ignition temperatures of organic compounds with particular emphasis on lubricants. C. E. Frank, A. U. Blackham and D. E. Swarts. N.A.C.A. Technical Note* 2848.

The study of spontaneous ignition characteristics of organic compounds has been extended to include various types of lubricants by using a spray-injection as well as a dropwise-addition procedure.—(34.1.1).

NOTE:—The Accessories list of the Science Museum Library for 3rd January 1953 includes "United States: National Advisory Committee for Aeronautics" Technical Note 2567 and onwards. The Library reference is TU 5888 B.Q.

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# THE AERONAUTICAL QUARTERLY

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